Economic potential and sectoral impacts of forest-based climate change mitigation

Integrated analysis in a global multi-sectoral land use model

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von
M.Sc. Forestry Michael Krause

Präsident der Humboldt-Universität zu Berlin:
Prof. Dr. Jan-Hendrik Olbertz

Dekan der Lebenswissenschaftlichen Fakultät:
Prof. Dr. Richard Lucius

Gutachter:
1. Prof. Dr. Dr. h.c. Harald von Witzke
2. Prof. Dr. Hermann Lotze-Campen
3. PD Dr.-Ing. Rüdiger Schaldach

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Dedicated to Ursula Krause,
who taught me invaluable lessons
about the important things in life.

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Abstract

The 21st century entails a range of outstanding challenges in the use of global land resources. The land use, land use change and forestry sector has been confirmed by the Intergovernmental Panel on Climate Change to hold significant potential to mitigate climate change. Avoiding deforestation in the Tropics and Subtropics and sequestering carbon through additional afforestation and forest management are highlighted to be of primary importance. The first challenge particularly in developing and transition countries is to give priority to forest-based climate change mitigation such as avoided deforestation while there is increasing competition for scarce productive land for the production of food, feed, fibre, bioenergy and timber and the provision of other ecosystem services. The second challenge is to ensure the increase in production in agriculture and forestry which is required to match with the increasing global demand for agricultural and wood commodities. The key concern is to produce enough food to cope with the increasing consumption per capita of the growing world population. The third challenge pertains to assessing the environmental and economic impacts of required production boosts through technological change, increase in inputs, change in management, international trade and managed land expansion if forest-based climate change mitigation is pursued. A key question relates to the foregone benefits in agriculture and forestry and the potential of climate change mitigation programmes in forests.

The doctoral thesis has investigated the climate change mitigation potential of global forests in normative policies and market-based programmes. The thesis has also analysed the economic and environmental impacts on competing agriculture and forestry land uses in terms of foregone benefits in sectoral production. Beside sectoral production cost changes, the shifts in land use patterns, change in required crop yields, managed forest establishment and wood harvest intensity have been analysed and discussed.

The global economic land use model MAgPIE ('Model of Agricultural Production and its Impact on the Environment') simulates spatially-explicit land use and land use changes and the costs of agricultural production to satisfy a prescribed demand. Endogenous technological change increases crop yields at additional cost, if required, and international trade allows relocating the production to regions with cost advantages. The model has been extended methodologically by the 'Forestry' sector to MAGPIE-F and by a consistent spatially-explicit data base on land use areas. Other extensions comprise spatially-explicit growing stocks and forest vegetation carbon stocks, the definition of wood production and associated costs in the forestry sector, trade as well as statistical models on forest product consumption. The land allocation is based on the productivity of land in different uses and the resulting relative total cost reductions from producing commodities or providing climate change mitigation as ecosystem services. Results from mitigation scenarios have been compared to baseline scenarios for different time horizons up to the year 2100.

The results show the limited climate change mitigation potential of normative forest conservation in tropical regions at low additional costs in agriculture. Latin America benefits from sufficient land endowments and lower increases in crop demand than in Sub-Saharan Africa leading to relatively low baseline deforestation. The link of the increase in crop production to technological change is emphasized to be strongest in Sub-Saharan Africa connected to the commodity demand of a highly growing population. In contrast to the low mitigation potential, the importance of providing other ecosystem services, i.e. biodiversity conservation in undisturbed natural forests has been highlighted. The economic potential of market-based climate

change mitigation, primarily from avoided deforestation, significantly exceeds that of normative forest conservation programmes in Latin America and Sub-Saharan Africa depending on the carbon price level. The sensitivity to carbon price development has been shown. Intra- and inter-regional carbon emission leakage reduces the global economic potential of climate change mitigation in forests. Results reveal that the implementation of programmes for avoided deforestation and afforestation / reforestation together are required to minimize the negative effects of incentivized afforestation in terms of direct or indirect clearing of natural forests.

The general conclusions pertain to the 1) need for high rates of yield increase predominantly in Sub-Saharan Africa as a general precondition for successful avoided deforestation programmes, 2) increased threat of international carbon emission leakage from implementing climate change mitigation programmes and liberalized trade of timber and wood products, 3) requirement of a better link between normative forest conservation to sustain multiple ecosystem services and market-based avoided deforestation programmes as source to co-finance normative forest conservation, 4) high economic potential of climate change mitigation from integrating of afforestation / reforestation and avoided deforestation programmes at moderate costs in forestry, and 5) additional research needs to account for considerable uncertainties from growth and cost parameters, model processes and unaccounted factors.

Zusammenfassung

Das 21. Jahrhundert bringt in Bezug auf die Nutzung der globalen Landressourcen eine Reihe von bedeutsamen Herausforderungen mit sich. Der Weltklimarat bestätigt das wesentliche Treibhausgas-Mitigationspotential des globalen Landnutzung, Landnutzungsänderung und Forstwirtschaft ('LULUCF') Sektors um dem anthropogen verursachten Klimawandel zu begegnen. Die vermiedene Entwaldung in den Tropen und Subtropen, zusätzliche Bindung von Kohlenstoff aus der Atmosphäre durch Aufforstungen sowie die Rolle der Forstwirtschaft wird herausgehoben. Die erste Herausforderung betrifft die Umsetzung der genannten Mitigationsmaßnahmen speziell in Entwicklungs- und Transistionsstaaten in den Tropen und Subtropen. Die Nutzungskonkurrenz um produktives Land wächst bereits ohne Berücksichtigung von Flächen für Klimaschutzmaßnahmen als Ökosystemleistung, um die aktuelle Produktion von landwirtschaftlichen (Nahrungmittel, Futter, Fasern, Bioenergie) sowie forstlichen Gütern (Rundholz und Gehölzbiomasse) sicher zu stellen, neben der Bereitstellung von anderen Ökosystemleistungen. Die zweite Herausforderung betrifft die Sicherstellung der zukünftigen Produktion von landwirtschaftlichen und forstlichen Gütern, welche ansteigen muss, um mit dem geschätzten Anstieg in der Nachfrage nach diesen Gütern mitzuhalten. Eine entscheidende Frage betrifft die höhere Produktion zur Sicherstellung der Ernährung einer wachsenden Weltbevölkerung mit steigendem pro-Kopf-Verbrauch an Nahrungsgütern. Die dritte Herausforderung betrifft die Einschätzung der zu erwartenden ökonomischen und die Umwelt betreffenden Auswirkungen von wald-bezogenen Klimaschutzmaßnahmen. Die ökonomischen und die Umwelt betreffenden Auswirkungen sind verknüpft mit zusätzlichen produktionssteigernden Maßnahmen in der Land- und Forstwirtschaft wie technischem Fortschritt, erhöhtem Einsatz von Produktionsfaktoren, verbessertem Management, internationalem Handel und der Ausdehnung der bewirtschafteten Flächen in verfügbares ungenutztes Land. Eine Schlüsselfrage hierbei betrifft die Höhe der Verzichtskosten, dem entgangenen Nutzen, im Landwirtschafts- und Forstwirtschaftssektor durch waldbezogene Klimaschutzmaßnahmen und das ökonomische Potential dieser Maßnahmen.

Die vorliegende Dissertation hat das ökonomische Potential von waldbezogenen Klimawandelschutzmaßnahmen untersucht und dabei zwischen normativen Waldschutzpolitikmaßnahmen und markt-basierten Klimaschutzprogrammen unterschieden. Weiterhin wurden die ökonomischen und die Umwelt betreffenden Auswirkungen auf die um Landressourcen konkurrierenden Sektoren Landwirtschaft und Forstwirtschaft analysiert. Der Fokus lag auf der Analyse und Diskussion der Verzichtskosten in der Güterproduktion, den Änderungen in Landnutzungsmustern und benötigtem technischen Fortschritt, der notwendigen Etablierung von zusätzlicher Wirtschaftwaldfläche und Änderungen in der Waldbewirtschaftung sowie Intensivierung der Holzernte.

Das globale ökonomische Landnutzungsmodell MAgPIE ('Model of Agricultural Production and its Impact on the Environment') simuliert räumlich-explizite Landnutzung und Landnutzungsänderungen und die Kosten landwirtschaftlicher Produktion unter gegebener Nachfrage nach Gütern. Landwirtschaftliche Erträge werden bei Bedarf durch endogenenen technischen Fortschritt unter zusätzlichen Kosten verbessert und internationaler Handel erlaubt die teilweise Verlagerung der Produktion in Regionen mit Kostenvorteilen. Das Modell MAgPIE-F enthält methodische Erweiterungen durch die Implementierung des Forstwirtschaftssektor und eine konsistente räumlich-explizite Datenbank zu Landnutzungsflächen. Die Erweiterungen umfassen weiterhin räumlich-explizite Schätzungen zu Vorräten und gebundendem Kohlenstoff in ober- und unterirdischer Biomasse in Waldvegetationstypen, die Definition von Optionen der

Holzproduktion, heutige und zukünftige Kosten der Holzproduktion, internationaler Holzhandel sowie statistische Modelle zur globalen Holznachfrage. Die Landallokation zu konkurrierenden Nutzungen basiert auf der Produktivität des Landes in verschiedenen Nutzungen und den daraus resultierenden relativen Gesamtkostenersparnissen in der Produktion von Gütern und Bereitstellung von waldbezogenen Klimaschutzmaßnahmen als Ökosystemleistungen. Ergebnisse aus Szenarien zu Klimaschutzmaßnahmen wurden verglichen mit Referenzszenarien über verschiedene Zeithorizonte bis zum Jahr 2100.

Die Ergebnisse verweisen auf ein begrenztes Mitigationspotential normativen Waldschutzes zu geringen zusätzlichen Kosten in der Landwirtschaft in tropischen Regionen. Lateinamerika profitiert von ausreichenden Landreserven und geringerem Anstieg in der Nachfrage nach landwirtschaftlichen Gütern als in Sub-Sahara Afrika, so dass die Referenzentwaldung moderat ausfällt. In Sub-Sahara Afrika wird für den benötigten Produktionsanstieg für landwirtschaftliche Güter deutlich der größte Zuwachs an technischem Fortschritt nötig im Vergleich zu anderen Regionen. Dies ist durch die Nachfrageentwicklung in der Zukunft und wiederum durch den signifikanten Bevölkerungszuwachs begründet. Im Gegensatz zum geringen Mitigationspotential wurde die Wichtigkeit des normativen Waldschutzes für die Bereitstellung anderer Ökosystemleistungen hervorgehoben, z.b. dem Biodiversitätsschutz in intakten Naturwäldern. Das ökonomische Potential eines kohlenstoffmarkt-basierten Programms zur vermiedenen Entwaldung übersteigt das des normativen Waldschutzes in Lateinamerika und Sub-Sahara Afrika deutlich in Abhängigkeit vom Niveau des Kohlenstoffpreises. Allerdings sind diese Ergebnisse sehr sensitiv gegenüber Änderungen in der Entwicklung des Kohlenstoffpreises über die Zeit. Die intra- und interregionale Verschiebung von Emissionen aus Entwaldung an anderer Stelle dämpft das ökonomische Potential. Die Ergebnisse zeigen, dass die Umsetzung von integrierten Programmen zu vermiedener Entwaldung und Aufforstungen benötigt werden, um negative Effekte wie Entwaldung von Naturwald zur Aufforstung zu minimieren.

Die generellen Schlussfolgerungen betreffen 1) den Bedarf an substantieller Ertragssteigerung hauptsächlich in Sub-Sahara Afrika als allgemeine Voraussetzung für die erfolgreiche Umsetzung eines Programmes zur vermiedenen Entwaldung, 2) die erhöhte Gefahr der internationalen Verschiebung von Emissionen aus Entwaldung an anderer Stelle durch die Umsetzung eines Programmes zur vermiedenen Entwaldung und der schrittweisen Liberalisierung des Holzhandels, 3) die Notwendigkeit der besseren Verlinkung von normativem Waldschutz zum Schutz multipler Ökosystemleistungen und markt-basierten Mitigationsprogrammen als Quelle zur Kofinanzierung des Waldschutzes, 4) das hohe ökonomische Potential integrierter Klimaschutzprogramme zu moderaten Verzichtskosten hauptsächlich in der Forstwirtschaft, sowie 5) die Notwendigkeit zusätzlicher Forschung bezüglich der wesentlichen Unsicherheiten in Parametern, Modellprozessen und durch unberücksichtigte Faktoren.

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1 Introduction

1.1 Research rationale, research questions and objectives

1.1.1 Research rationale

Global competition for land and the economic potential of forest-based climate change mitigation

It is widely recognized that the coexistence of sustainable use and conservation of natural resources, like forests, is fundamental for environmental sustainability. Nevertheless, the rate of global deforestation over the past 20 years has been 0.2 % per year (FAO, 2010) while the rate of tropical deforestation[1] amounts to 0.5 % per year (FAO, 2010). Thus deforestation has been significant and is associated with a significant rate of biodiversity loss (Butchart et al., 2010; Gorenflo and Brandon, 2005) despite the emphasized role of forest-based climate change mitigation and biodiversity conservation on the political agenda (United Nations, 2010, 2013).
Historical estimates credit 17.4 % of global CO_2 emissions to forestry including deforestation (IPCC, 2007). More recent estimates confirm that deforestation is responsible for 12 % of the global emissions, not accounting for soil carbon (Van der Werf et al., 2009). Global food crop yields need to more than double by 2050 given the expected population increase of 9 to 11 billion by 2050 (Nakicenovic and Swart, 2000). Actual yields have increased by 1.7 % per year on average over the past 50 years (Alexandratos et al., 2012). Still, agricultural expansion is the main driver of deforestation, particularly in the Tropics, where it explains 96 % of deforestation, though in combination with other land uses (Geist and Lambin, 2002). Additionally, the forest is in demand for wood products, fiber, fuel, non-fuel wood production, and infrastructure and the provision of ecosystem services other than carbon sequestration, carbon storage and biodiversity (Smith et al., 2010; Eliasch, 2008; Roberts, 2008; van Velthuizen, 2007; Lotze-Campen et al., 2008, 2010a). It is uncertain if the trend of increased land use efficiency in global timber production, primarily through timber plantation establishment in tropical regions, persists (FAO, 2006, 2010). If the historical trend continues (FAO, 2006, 2010), there is uncertainty whether the increase in timber consumption worldwide can be absorbed, which exerts pressure on unused and extensively managed natural forests. In addition, deforestation has been rooted in misguiding policies like agricultural subsidies (Angelsen and Kaimowitz, 2001; Yaron, 2001) and timber trade policies (Barbier et al., 1994).

The existing pressure on forest lands and the fact that forests may play a significant role in climate change mitigation have given rise to the comparison of scientific studies on the economic potential of global forests for climate change mitigation in IPCC's Assessment Report 4 (IPCC, 2007). The economic potential accounts for the full biophysical potential, defined by land availability and productivity, and the economic costs. It excludes institutional or socio-cultural constraints and is therefore higher than the market mitigation potential but lower than the

[1] The regions South America, Central America, South and South-East Asia, Oceania, Africa are considered (FAO, 2010).

biophysical potential (Smith, 2012).
The economic potential of emission mitigation through Avoided Deforestation (AD) is a debated issue in the policy and research arena (Forneri et al., 2006; Kindermann et al., 2008). There have been studies which focus on the mitigation potential and costs of carbon sequestration at different carbon price levels (Sedjo et al., 2001), or the increase of forest rents to avoid deforestation (Angelsen, 2010). IPCC (2007) compiles top-down and bottom up study approaches (Sathaye and Andrasko, 2007; Sohngen and Sedjo, 2006), global partial or general equilibrium models and aggregated regional engineering studies, which have different results on the economic mitigation potential of AD and Afforestation and Reforestation (AR) (IPCC, 2007). Modelling combined climate change mitigation activities is needed to address uncertainties from current modelling exercises without integrated AD, AR and forest management modelling at a similar level of detail (IPCC, 2007). Questions remain concerning the increasing population in the future, the production level to be ensured at which costs, and the spatial patterns which shift among regions. The present doctoral thesis strives to answers to the questions above.

Impacts of climate change mitigation on agriculture and forestry

The economic potential of forest-based climate change mitigation results from correcting the global failure of not valuing avoided carbon emissions and carbon removals by sink. Pricing climate change mitigation as a forest ecosystem service aims at the socially optimal allocation of resources, foremost land to competing uses such as agriculture, forestry and climate change mitigation. From another perspective, the land resource allocation to AD or AR for climate change mitigation leads to new challenges in global food and wood commodity supply. The forest-based emission mitigation potential (IPCC, 2007) is associated with food and wood production losses or additional costs to ensure the supply is adjusted to meet the demand. The opportunity costs to climate change mitigation, the foregone benefits from not using the land for commodity production constitute sectoral economic impacts. They accrue from required productivity increase and costs in agriculture and forestry if land is re-allocated. If the production of food and wood commodities is shifted into other natural ecosystems (Miles and Kapos, 2008), negative feedbacks may accrue in terms of carbon emission leakage (Lambin and Meyfroidt, 2011; Ostwald and Henders, 2014) and the dwindling of other ecosystem services (Ostwald and Henders, 2014).

Food and wood commodity trade constraints may reinforce regional shortages in supply at constant demand if not counterbalanced by research and development (Schmitz et al., 2011). It has been concluded in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Rokityanskiy et al., 2007; Sathaye and Andrasko, 2007; Sohngen and Sedjo, 2006; Benitez-Ponce, 2005) that the economic mitigation potential of forests and land use change (areas and area changes, carbon benefits and costs including opportunity costs for land) in global studies needs further analysis. The economic impact in terms of foregone net benefits of additionally reserved forest land for climate change mitigation to the next best land use type may constitute an important economic cost component (van Kooten et al., 2004; Kindermann et al., 2008). The opportunity costs borne by the agriculture and forestry sectors have not been sufficiently investigated at global scale. Golub et al. (2009) use a Computable General Equilibrium (CGE) model to estimate the opportunity costs at aggregate level. van Kooten et al. (2004) explicitly include the opportunity costs of land in the cost of carbon sequestration through forestry projects in a metastudy. Sathaye et al. (2005) describe welfare gains and losses from climate change mitigation activities in only the forest sector[2]. Kindermann et al. (2008) estimates costs of AD from forest sector's perspective. The doctoral thesis attempts to shed light on the distribution of opportunity costs in the agriculture and forestry sectors attributed to market-based climate change mitigation programmes in forests.

Commonly, studies on climate change mitigation options and potentials in land use generate carbon prices endogenously in connection with energy system models and macroeconomic models. The carbon shadow price from equating emission abatement cost and social damage cost is generated (Sedjo et al., 2001). The underlying rationale for price development is that carbon prices trace marginal social damage costs, the full global costs of emitting an additional unit of carbon (or equivalent) over the lifetime in the atmosphere. Sedjo et al. (2001) refers to shadow prices of carbon since global carbon market prices from trade in carbon markets are conceptually different and the willingness to pay for emission mitigation measures is grasped. Alternatively, future carbon prices can be taken as given in a scenario analysis (Kindermann et al., 2008), which is considered a reasonable approach.

Schmitt et al. (2009) highlight the insufficiency of forest areas set aside for conservation within global priority areas for nature conservation. This coincides with a cross-sectional study which provides economic arguments for the conservation of nature, *inter alia* tropical natural forest. Based on the total economic value the study by Balmford et al. (2002) shows a benefit-cost ratio of conservation of 100 to 1. In contrast, large-scale normative forest conservation has been criticized concerning the lack of enforcement in parallel to involving of local stakeholders (Hayes and Ostrom, 2005; Schwartzman et al., 2000). Thus, the success of forest conservation programmes strongly relies on minimizing the economic impacts on foregone alternative land uses, the sectoral losses from forest conservation. The economic impacts may accrue in terms of opportunity costs in the agriculture sector due to restrictions of suitable land available land for land expansion. However, the economic impact of normative forest conservation for climate change mitigation has not been widely analysed thus far since it requires internationally agreed upon definitions of forest conversion, targets and deadlines for reducing deforestation (Forneri et al., 2006). Gorenflo and Brandon (2005) find that the expansion of protected areas for biodiversity conservation is not necessarily a compromise concerning expanded agricultural area, since the majority of conserved land possesses low suitability for crop cultivation. Forest land with low productivity does not significantly contribute to expanded food and feed production and is therefore not given priority in cropland expansion. A similar question could also be asked on the impact of conserving high value forests, such as intact and frontier forests as defined by Bryant et al. (1997) and Greenpeace (2005), for climate change mitigation even without yet established institutional prerequisites for immediate translation into action. The present study fills the research gap by estimating the economic impact on agriculture if normative conservation efforts are expanded to tropical natural forests which are prioritized for high biodiversity conservation (Brooks et al., 2006) and carbon storage (Jackson et al., 2008).

Modelling forestry and agriculture sectors

The modelling of the forestry sector as stand-alone sector has already been dealt with in the 1990s. Global applications range from timber supply (Sedjo and Lyon, 1990; Sohngen et al.,

[2]It is hereby understood that the 'forest sector' embraces the 'forestry sector' which can be defined 'to include all economic activities that mostly depend on the production of goods and services from forests' (Lebedys, 2004, p.3).

1999), wood fiber supply (Bull et al., 1998), forest carbon supply (Sedjo et al., 2001) to demand-supply interactions in the global forest products markets (Buongiorno, 2003).

The modelling of the forestry and agriculture sectors together at similar level of detail and together in a spatially-explicit bio-economic modelling framework was not widespread in the past (Lambin et al., 2000; Heistermann et al., 2006; Kindermann et al., 2008) but is identified as a field requiring improvement (Boettcher et al., 2008; Havlik et al., 2011). Sectors not covered explicitly create a flaw in the results on the dynamics of land use area and its patterns. The additional demand for land has been commonly approximated by constant land use areas prescribed for alternative land uses (Lotze-Campen et al., 2008). In contrast, efforts to couple those sectors at global scale in one spatially-explicit modelling framework at a comparable level of detail are still limited (Havlik et al., 2011).

The competition for land in the agriculture sector compared to other land-intensive sectors, primarily the forestry sector, was not explicitly modelled in the existing agricultural land use optimization model, the Model of Agriculture and its Impact on the Environment (MAgPIE) (Lotze-Campen et al., 2008). The doctoral thesis fills the gap in the existing model by developing a simple representation of the global forestry sector and by this means contributes to further research.

While production cost differentials per hectare can be based on the heterogenous distribution of crop yield across spatial units (Lotze-Campen et al., 2008), spatial transport costs have not been included due to the lack of spatially-explicit transport distances and methods to translate them into spatially explicit tranport costs. The current study presents a method to derive spatial transport cost data from spatially-explicit transport distances (Nelson, 2008) and average transport cost data for agricultural commodities.

The economic potential of climate change mitigation in forests and economic impacts on land use sectors depends on the restrictions of available suitable land for agricultural or forest land expansion. The consistent definition of the land resource endowment across land uses and the magnitude of land available at the extensive margin for the expansion of managed land into unused land is a prerequisite for multisectoral land use modelling. Studies commonly investigate land use and land cover classes (Geist and Lambin, 2006) and follow an approach that uses rules to identify remaining land types after cropland, grassland and forest land have been substracted beside topographic, soil, and climate information to define available land for managed land expansion (Fischer et al., 2002). The land use areas in the existing MAgPIE have not been consistently represented hindering the implementation of the forestry sector. Therefore, there has been a need for the development of a consistent land use database by a land use budgeting approach, and the estimation of available land for sectoral expansion.

1.1.2 Research questions and objectives

A set of research questions addresses the knowledge gaps identified from the literature review in three research fields,

- The benefits of normative forest conservation programmes and market-based climate change mitigation programmes in forests:
  - Q1. What are the benefits of target-oriented natural forest conservation strategies in terms of avoided deforestation and avoided net carbon emissions from land use change?

Q2. How does forest carbon supply from market-based climate change mitigation programmes in forests respond to forest carbon prices?

Q3. What is the economic potential of market-based climate change mitigation programmes in forests compared to other studies?

- The economic impacts of normative forest conservation programmes and market-based climate change mitigation programmes in forests:

  Q4. What are the economic impacts of target-oriented natural forest conservation strategies on agricultural production in Sub-Saharan Africa, Latin America and Pacific Asia?

  Q5. What are the economic impacts of market-based climate change mitigation programmes such as avoided deforestation and afforestation / reforestation on agriculture and forestry?

  Q6. How do sectoral production patterns and required yield increase in agriculture and forestry change to meet future demand for food, feed and wood commodities?

- The implementation of the forestry sector in a multi-sectoral global land use optimization model:

  Q7. What is the magnitude of land area available for agricultural and forestry expansion and how is the spatial distribution?

  Q8. How can forestry sector dynamics, in particular the timing and costs of forest establishment, tending and harvest decisions be incorporated in a recursive dynamic agricultural land use optimization model?

The research questions led to formulating an overall objective which the present doctoral thesis strives to attain.

The overall objective is to contribute to the analysis of the economic impacts of forest-based climate change mitigation on competing land uses and the potential of global forests for climate change mitigation.

The overall objective is broken down into a set of specified objectives ascribed to the research questions in three fields of research:

- The benefits of normative forest conservation programmes and market-based climate change mitigation programmes in forests:

  O1. To analyse and assess the benefits of normative natural forest conservation programmes in terms of avoided deforestation and avoided net carbon emissions from land use change

  O2. To derive forest carbon supply estimates and to analyse how market-based climate change mitigation activities respond to changes in forest carbon prices

  O3. To contrast the economic potential of forest carbon supply from climate change mitigation activities to other studies

- The economic impacts of normative forest conservation programmes and market-based climate change mitigation programmes in forests:

O4. To analyse and assess the economic impacts of natural forest conservation strategies on agricultural production in tropical regions

O5. To analyse and assess the economic impacts of market-based climate change mitigation programmes in forests on agriculture and forestry

O6. To analyse changes in sectoral production patterns and required yield increase

- The implementation of the forestry sector in a multi-sectoral global land use optimization model:

O7. To develop a land use database by means of a land budgeting approach and to derive consistent estimates on bio-physically available land for sectoral expansion

O8. To conceptually develop and implement the forestry sector in an existing global agricultural land use optimization model

1.2 Methodology of analysing the global land use sectors and the impacts of climate change mitigation

1.2.1 Theoretical background

The methodological foundation of the doctoral thesis rests on various theories that guide analysing the impacts of climate change mitigation activities and the competition of global land use sectors with special regard to the implementation of the forestry sector.

Most importantly, the **micro-economic theory of market externalities** applied to forest land use argues that inefficient forest land allocation takes place due to unaccounted externalities of forest land use to society. The theoretical background dates back to Pigou (Pigou, 1920) who states that the private industrial production may exert costs to society in terms of air pollution that are not accounted for privately. If the private and social costs of production differ, the profit-maximising private production decision is non-optimal from a societal perspective. More specific to the land use context, an externality can be considered as uncompensated cost or benefit to society stemming from private land use decision making (Arriagada and Perrings, 2009).

The economic value of forests has traditionally been grasped via marketable products such as timber and non-timber forest products, which provide direct private use value. Other forest ecosystem services important for human well-being such as regulating (e.g., climate, water), cultural (e.g., recreation, spiritual) and supporting (e.g., soil formation) services, have been recognized as valuable and scarce services (Gomez-Baggethun et al., 2010; Duraiappah et al., 2005; Adeel et al., 2005; Diaz et al., 2006) but are not accounted for privately. The theory of externalities thus explains that ecosystem services are undersupplied to local or global beneficiaries because markets do not exist, or market development is in its infancy, which is referred to as market failure (Arriagada and Perrings, 2009).

By its characteristics, climate change mitigation through carbon sinks and storage by retaining forests, improving management and AR is a non-marketed positive benefit, externality, provided to society by land users. In turn, the economically rational land user aims at maximizing his welfare which in the absence of markets for forest carbon may lead to deforestation, unsustainable forest management and little AR which leads to undersupply of forest from society's perspective (Angelsen and Wertz-Kanounnikoff, 2008).

Forest-based climate change mitigation is characterized by being a public good with non-rival and non-excludable characteristics, a special type of externality (Cornes and Sandler, 1996). The first characteristic, non-rivalry, exists because the benefit of climate change mitigation in forests to one part of society in terms of avoided damage costs from climate change does not constrain the benefit to another part of society. Forest-based climate change mitigation does not exclude a part of global society which is the second characteristic of public goods. This leads to the challenge of dealing with freeriding behaviour, reaping the benefits without bearing a share of the costs associated with climate change mitigation (Pearson, 2011; Burniaux et al., 2009).

The internalization of externalities (Arriagada and Perrings, 2009; Duraiappah, 2006) follows the basic principle that monetary value is ascribed to the positive or negative consequences of private decision making which impact the society. The monetary value of forest-based climate change mitigation activities helps grasping them as cost and revenue stream in economic accounting. Policy instruments designed to promote forest conservation, improved forest management and additional AR are aimed at climate change mitigation at socially optimal instead of the privately optimal magnitude. They range from direct regulation (normative or command and control instruments) to market mechanisms (taxes, subsidies, transfer payments) (Forneri et al., 2006; Arriagada and Perrings, 2009). Taxes and subsidies may lead to economic inefficiencies over the long run eroding environmental services, e.g. subsidies for AR may lead to deforestation of natural forests (Yaron, 2001). Economic inefficiencies are induced by the interference of governments in existing markets. This interference may e.g. lead to financial incentives for deforestation (Pearce and Moran, 1994) and can be seen as a source of market distortion (Duraiappah, 2006). Transfer payments, such as payments for ecosystem services, often exist in a monopsony if governments function as sole surrogate demanders (Salzman, 2005) or single private companies pay for ecosystem services (Arriagada and Perrings, 2009). There is a set of further policy instruments for forest conservation compiled by Angelsen (2010).

Though competitive forest carbon markets are emerging[3], the creation of fully functioning private markets for climate change mitigation in forests, in terms of carbon storage and sequestration as ecosystem services, is difficult to achieve due to the characteristic of climate change mitigation as public good[4]. Therefore, the role of governments in setting an enabling climate policy framework remains crucial to stimulate the demand for forest carbon which ensures the value added of AD and AR for climate change mitigation.

An overarching characteristic of forest-based climate change mitigation approaches is the potential displacement, leakage, of carbon emissions. Emissions result directly from relocating land use activities or indirectly from the substitution of goods in markets. The concept of leakage and Indirect Land Use Change (ILUC) are similar but emerge from different realms (Ostwald and Henders, 2014; Lambin and Meyfroidt, 2011).

The placed value on AD and additional AR aims at correcting the economic failure and

[3] Voluntary carbon markets develop in parallel to the Kyoto compliance market for emission offsets through AR, with corporate social responsibility being the main driver of private demand for forest carbon credits (Milder et al., 2010).

[4] Other obstacles comprise the lack of appropriate institutions across political jurisdictions and largely missing private land property rights (Salzman, 2005)

associated inefficient land allocation from the society's perspective (Figure 1.1). The general mechanism of land allocation to different uses plus AD and AR can be explained by the **theories on differential land rent and location rent** by Ricardo and v.Thuenen respectively (Ricardo, 1891; Von Thuenen, 1966; Lambin et al., 2000). Differential land rent is based on diminishing marginal returns due to diminishing land productivity in an economic activity. According to Ricardo, the society takes sucessively worse quality, inferior, land into agricultural cultivation as the society's total food consumption increases over time and pressure on unused land is expected to persist. Superior land earns rent in contrast to land at the margin of being used which does not earn rent at all (van Kooten and Bulte, 2000). However, the classical differential rent theory is extended by the modern economic rent theory that defines rent as the payments beyond those to keep land in the present land use. Land is kept in its current use if the opportunity costs, the value of foregone or given up benefits of not pursuing alternative next best land uses, is paid as so-called transfer payments to the land user. Though land is an immobile production factor, it is not totally inelastic in supply as presupposed in Ricardo's theory and shifts between land uses are possible. V. Thuenen's location rent is based on the gradient of average transport costs as function of the distance to markets. Both theories combined ensure that land is devoted to the activity with the highest possible rent which is influenced by the costs to transport goods to market centers.

The land allocation between agriculture and forestry needs to deal with the peculiarity of different time horizons of agricultural commodity and wood production. The investments in long production horizons in the forestry sector compared to investments in agriculture require the result of a multiperiodic economic analysis (Dowdle, 1962; Samuelson, 2012; Kant, 2003). The capitalized value of barren forest land, the Land Expectation Value (LEV) (Faustmann, 1995; Chang, 1981, 1983; Straka and Bullard, 1996) needs to be made comparable to the annual land rents in agriculture. The LEV in its classical version by Martin Faustmann, a German Forester in 1849 (Faustmann, 1995) is restrictive regarding the allocation of barren timber land to timber land. In timberland markets it expresses the willingness to accept for a parcel of timberland from a land owner's perspective compared to the willingness to pay from the perspective of a buyer of timberland. However, the LEV has also been used for comparing land allocation options across sectors (Liao and Zhang, 2008) and the economic comparision of agriculture and forestry (Chisholm, 1963; Deininger and Byerlee, 2011). The annual agricultural land rents could be capitalized by means of the LEV. Alternatively, the forest land rent can be derived as annuity value of the LEV which denotes the equal periodic stream of income per hectare that can be generated in perpetuity. The discount rates for analysing the mitigation potential in forests should reflect the social costs and benefits and thus be lower than the private discount rate (IPCC, 2007).

However, the multiperiodic economic analysis comes with a significant weakness, the uncertainty of future output and variable factor prices. The **theory of rational expectations**, first proposed in the 1960s by Muth describes economic activities where the outcome depends partly on what agents expect to happen by their best guess of the future (Muth, 1961). They make use of all available information from previous experiences, which is to say that their expectations equal true statistical expected values. The theory of rational expectations is based on the standard economic assumption that economic agents maximize their utility or profits. The theory is useful (a) to explain the adjustment of contemporary behaviour of economic agents such as land users in agricultural supply and land allocation decisions (Eckstein, 1984), (b) to determine expected agricultural commodity prices by future demand and supply interactions (Goodwin and Sheffrin, 1982; Irwin and Thraen, 1994), and (c) to allow for analysing the expected future development of forest commodity demand or prices and the timing of timber harvest (Berck, 1976). Forest land allocation to timber types aims at maximizing the LEV (Faustmann, 1995) based on rationally expected future streams of costs and revenues. The underlying theory deals with the economics of optimal stopping of land development under certainty (marginal revenue product versus marginal input cost of holding the land) and uncertainty without the assumption of perfect foresight (Davis and Cairns, 2012). For example, suppose that the current supply of roundwood in a global market equals the current demand for roundwood in equilibrium. The current supply in turn depends on the non-separability of the current merchantable timber harvest and forest establishment dated back several decades. The theory of rational expectations can be used to say that the actual future roundwood supply and demand will only deviate from the expectation if information unforeseeable at the time of taking the forest establishment decision causes a shock in the state of production or consumption of roundwood in the future.

The scope of analysing global land use sectors can be set by describing them as systems with states and processes and clear boundaries in spatial and temporal dimensions. The **general systems theory** which came into use in the mid 1950s describes a 'level of theoretical model-building which lies somewhere between the highly generalized constructions of pure mathematics and the specific theories of the specialized disciplines' (Boulding, 1956, p.197). It depicts the relationships among components of the defined system abstracted from a concrete situation or empirical knowledge (Boulding, 1956). However, a system does not necessarily have any connection to the 'real' world and constitutes an approximation of reality on land use sectors and the economic potential and impacts of climate change mitigation activities. Physical or conceptual boundaries distinguish a real-world system from the surrounding environment. Land use systems may comprise natural (physical) system components from the biosphere, geosphere and atmosphere and human (social) system components from the anthroposphere that interact with each other (Turner et al., 1993; Mendelsohn and Dinar, 2009). The social system may consist of land users or, expressed in a more abstract way, producers in economic sectors such as agriculture and forestry. They are economically, socially, culturally driven to maintain, modify or convert natural and anthropogenic ecosystems, e.g. by deforestation of tropical forests or by establishment and management of tropical forest plantations. The physical system component may be explicitly described by a combination of site characteristics such as soil types, topography, precipitation, and temperature (Fischer et al., 2002) to define land productivity in land cover types based on underlying land uses and the interaction with the atmosphere, such as the impact of climate change mitigation activities, e.g. avoided tropical deforestation, and the feedback of the atmosphere, e.g. CO_2 fertilization through global warming, on the biosphere and geosphere. Mitigated climate change feeds back to the social system via the natural system by means of the costs and benefits of respectively required activities.

1.2.2 Forest-based climate change mitigation in land use and land use change modelling

Modelling the role of climate change mitigation activities in forests and their economic potential and impacts on forestry and agriculture requires the modelling of land use and land use changes by land (re-)allocation decisions.

However, approaches and models developed vary in the literature with discipline, scale of analysis, and data availability. The Conversion of Land Use and its Effects (CLUE) model is a geographic land use change model which allocates land to different uses by a multi-scale approach and allocation rules based on empirical statistical relationships between explaining factors and historical land use and cover changes from national scale to grid cells (Verburg et al., 1999, 2002). Alcamo and Schaldach (2006) and Schaldach et al. (2011) use suitability criteria to allocate the agricultural crop production to spatially-explicit land parcels. The competition for natural resources between the major land use sectors including 'settlement and industrial', agriculture and forestry is modelled by means of a Multi Objective Land Allocation Algorithm (Schaldach and Koch, 2009; Eastman et al., 1995). In another modelling approach, the suitability-based land allocation results from the Integrated Model to Assess the Global Environment (IMAGE) modelling framework (IMAGE Team, 2001). Areas enter as regional aggregates via a land transition matrix into the CGE Global Trade Analysis Project (GTAP) model (Burniaux, 2002). Burniaux (2002) prescribes transitions of sectoral land area by the Special Report on Emissions Scenarios (SRES) scenario B2 (Nakicenovic and Swart, 2000).

Besides economy-wide modelling approaches where CGE models are coupled to spatially-explicit land use models (Hertel, 2009; Hertel et al., 2009), Partial Equilibrium (PE) models have been used to model the allocation of land in a specially-explicit or non-spatial way. The spatially-explicit PE model Global Biosphere Management Model (GLOBIOM) aims to maximize the sum of producer and consumer surplus in forest and agriculture sectors and but uses transition contraints (Havlik et al., 2011). In the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) the rate of land conversion to agriculture is determined by the crop price-based area response function and exogenous trends in harvested area are introduced to grasp factors not covered by direct crop price effects (Rosegrant et al., 2008). Sands and Leimbach (2003) shift land between crop, livestock and forest sectors relative to returns obtained, but lacks spatial explicitness in the Agriculture and Land Use (AgLU) model. Darwin et al. (1996) induce inter- and intra-class land shifts by climate, population growth and trade scenarios. Ronneberger et al. (2009a) assumes a constant harvested area over time in the model Kleines Land Use Model (KLUM). In the IMAGE modelling framework the change in the gap between potentially available land and current agricultural land leads to one of four prescribed land conversion types and a change in land prices (Bouwman et al., 2006).

Previous examples show that modelling land allocation across sectors and land uses at global and regional scale has a long history and comprises various approaches such as empirical-statistical, stochastic, dynamic simulation modelling which to discuss extensively hereafter is beyond the scope of the thesis. They are compiled by Irwin and Geoghegan (2001) and Heistermann et al. (2006). Schaldach and Priess (2008) review integrated regional to global scale models of the land system which simulate the interplay and competition between different land-use activities in a geographically-explicit way. Schmitz et al. (2014) give a comprehensive up to date overview of global agro-economic models that implicitly or explicitly account for the forest sector and land allocation across sectors and land uses.

Since the late 1990s climate change studies have been conducted from the forestry sector pespective to estimate the climate change impacts on timber markets (Sohngen et al., 2001), and the optimal management for carbon sequestration (Sohngen and Mendelsohn, 2003). Additional studies looked at carbon sequestration under carbon price regimes (Sohngen and Sedjo, 2006) and explicit policy incentives (Benitez-Ponce, 2005), and the costs of AD (Kindermann et al., 2006, 2008; Sohngen et al., 2008). The integrated forestry and agriculture sector perspective has been tackled to estimate the economic potential of global forests and land use change, carbon sequestration, impacts of carbon incentives, and climate policy impacts (Sathaye et al., 2005; Obersteiner et al., 2006; Rokityanskiy et al., 2007).

In general, the mechanism of land allocation to forests for climate change mitigation can be modelled based on the theories of Ricardo and v.Thuenen. The area accessed is a function of distance to markets and the land is heterogenous in productivity which is evenly distributed across the accessed area (Figure 1.1).

Panel 1 in Figure 1.1 shows the agricultural land allocation in a region where agricultural land is the managed land type that is predominant. The potential to generate positive land rents in managed land use after clearing natural forest is the major driver of deforestation at the 'new frontier' of managed land to accessible previously unused natural forest. The illustration is adapted from Hyde (2003, Fig.3.1) which describes a taxonomy of forest development.

Agricultural land allocation on accessible land takes place along the gradient of decreasing land rents A between 0 and EM as function of the distance to the market center approximated by decreasing accessibility of land. The periodic net value of growing a crop per hectare in perpetuity denotes the periodic land rent. The land heterogeneity thus does not distort the downward sloping trend. Point EM denotes the extensive margin or frontier between developed (agricultural) land and unused natural forest. At this point there is no deforestation taking place to meet the derived demand for agricultural land. The point EM indicates that the agricultural output price is sufficient to cover the marginal costs of output supply on the last hectare under cultivation while the average total costs equal marginal costs. Thus, zero land rent is generated to the farmer, i.e. rents to capital and labour inputs are already subtracted (van Kooten and Bulte, 2000, p.60).

The increase in output prices due to outward (to the right) shifts of the output demand curve[5] leads to increased derived demand for agricultural land, expressed by the outward (to the right) shift of curve A to A' and the shift of the extensive margin, the frontier, from EM to EM'. Managing tree-grown land plots at initial and at expanded wood demand F and F' does not generate competitive land rents to optimally re-allocate land from agriculture. Hyde (2003) argues that tree removal for agriculture is costly and therefore results in negative rents. It is assumed that at the 'new frontier' in panel 1 the opportunity costs of variable inputs (labour and capital) are simply too high and the value of harvestable wood commodities is too low to make forestry land use feasible.

For the ease of depiction, it is assumed that A' already bases on the adjusted outward shifted output supply curve from more land taken into production, the feedback on final output price and output quantity. The trade-off between expanding agricultural land or intensifying land use by technological change aims at achieving the boost in total output by minimized variable factor inputs associated with each of the activities[6]. The opportunity costs of variable factor inputs in cultivating an additional hectare of unused natural forest at the frontier determine the extent of manageable additional land area (Hyde, 2003). This holds, since intensification may be less costly in terms of variable inputs costs per unit output than land expansion. The

[5]Drivers such as population or income increases may cause the growth of demand for food (Mendelsohn and Dinar, 2009).

[6]Theoretically, the optimal, cost-minimizing variable factor combination between capital and labour for each additional hectare of land is defined by the point where the slope of the isoquant equals the slope of the isocost line depending on the change in relative marginal costs of factor inputs.

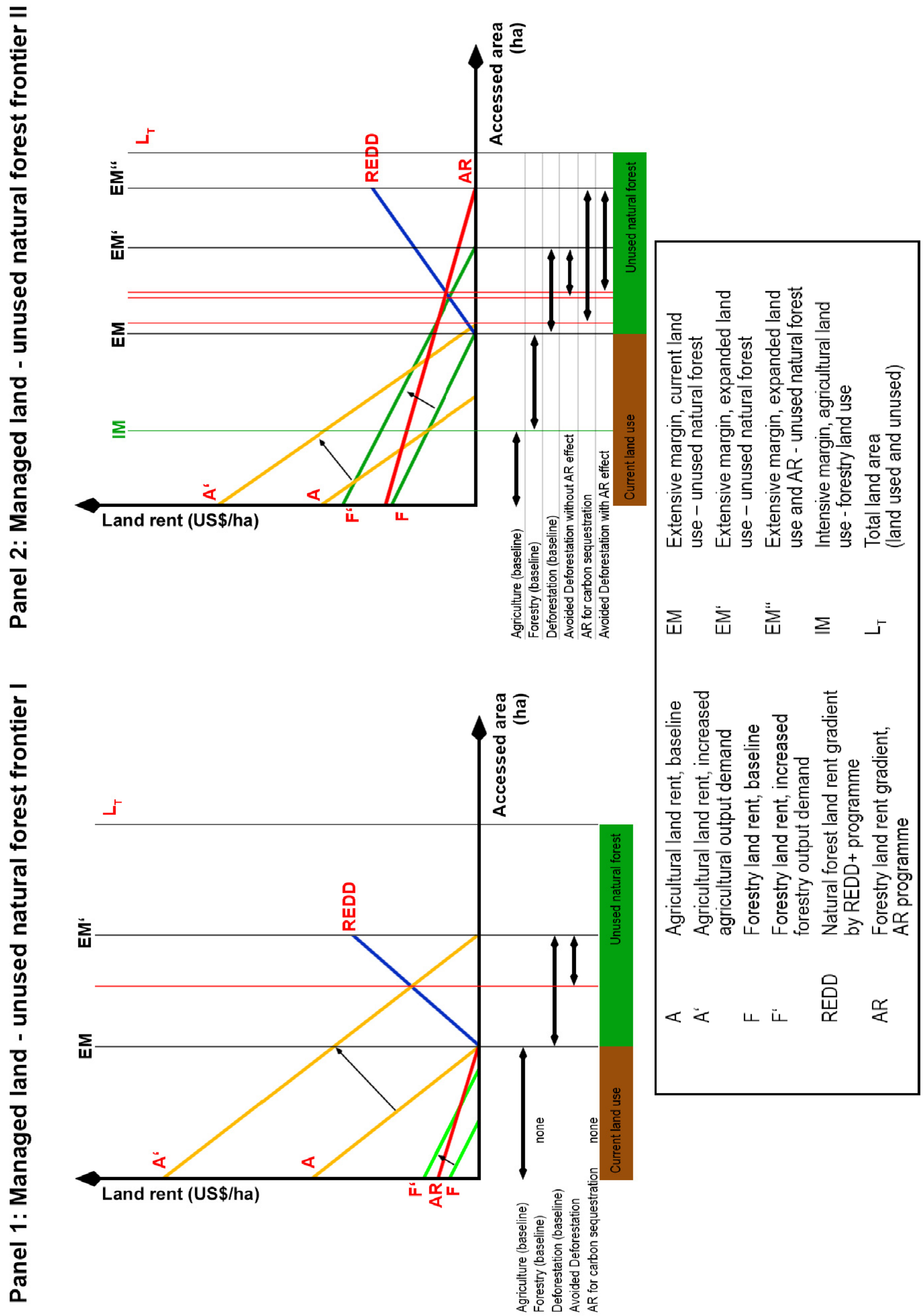

Figure 1.1: Land rents, deforestation and the social benefits of climate change mitigation in managed land - natural forest frontier regions

derived demand for additional agricultural land is thus linked to the magnitude of boosted agricultural land productivity from technological change and associated variable factor inputs (Dietrich et al., 2013) and the availability of variable inputs (Hyde, 2003). The derived demand for agricultural land area between 0 and EM' leads to the encroachment into unused natural forest land and conversion to managed land at the magnitude between EM and EM'.

The valuation of mitigated forest carbon emissions from AD via Reducing Emissions from Deforestation and forest Degradation plus the conservation of forest carbon stocks, sustainable forest management and enhancement of forest carbon stocks (REDD+) (Angelsen and Wertz-Kanounnikoff, 2008) raises the opportunity costs of deforestation. These oppportunity costs are ascribed to the forest land rent $REDD$ earned from the next best land use option, forest conservation. Depending on the price of forest carbon from REDD+, deforestation is offset at the magnitude indicated by 'Avoided Deforestation' in the graph. In the present example, the area of unused natural forest between the extensive margin EM' and the physically available area L_T cannot be monetarily valued via REDD+ because it does not not face the threat of deforestation or degradation.

AR for carbon sequestration on top of F' generates lower land rents at 0 than F' due to restrictions in AR carbon projects. Deviations in rotation length and monitoring requirements are assumed to reduce the financially optimal timing of harvest and increases variable input costs. However, forest carbon value is created which may exceed merchantable wood value.

Panel 2 in Figure 1.1 illustrates the land allocation in regions where agricultural and managed forest land development are contributing to deforestation. The 'mature frontier' of managed land to accessible unused natural forest land is adapted from Hyde (2003, Fig.3.3) of the taxonomy of forest development.

The efficient allocation of managed land is based on striving for the highest return to land, considering the competing land use options agriculture and forestry. Again, land rents per hectare decrease from 0 to the extensive margin EM while 0 to the intensive margin IM defines agricultural land area. The area of managed forest is allocated further from the market center from IM to EM as wood does not face the threat of perishing, and the costs of transport per unit and kilometer are lower than for agricultural commodities in this example.

Outward (to the right) shifts in both the derived demand for agricultural and managed forest land give rise to area changes at the intensive and extensive margins. At IM the changes in relative land rents determine the net increase or decrease of agricultural land at the expense of managed forest land. At the area between EM and EM' managed forest land is expanded into unused natural forest, making the land area denoted as 'Deforestation (baseline)' in Panel 2 of Figure 1.1 financially attractive for the production of wood commodities, primarily timber (Hyde, 2003)[7]. The figure only examplifies the magnitude of conversion of natural forest caused by managed forest land development but could also illustrate a share of unused land allocated to agriculture.

The magnitude of deforestation depends on the marginal costs of access which equal the benefits of accessing unused natural forest, i.e. the net revenues from one-time timber harvest and subsequent capitalized land rent of managed forest land use on the margin (Gouel and Hertel, 2007).

[7] It needs to be added that the definition of 'deforestation' from the conversion of natural forest to managed forest (timber plantations) depends on the country definition of 'forest'. Forest land may remain forest land but the area of natural forest may decrease and thus the inherent ecosystem services provided to society.

Incentives for AR for carbon sequestration shifts the demand for managed forest land further outwards and additional previously unused natural forest land is allocated up to the extensive margin at EM''. The example clearly shows the threat of additional deforestation coming from AR programmes for carbon sequestration, if natural forest conservation is not taken into consideration. Unused land that is not forest where afforestation could become viable is neglected.

AD programmes through REDD+ work similar to the 'new frontier', the opportunity costs of deforestation cause less natural forest to be converted to managed forest land. However, the magnitude of AD is likely to be smaller compared to the 'new frontier' because of the smaller carbon stock difference between managed and natural forest which generates less financial incentives. The magnitude of AD which could be valued in carbon markets is larger when AR activities are promoted ('with AR effect') and this case defines the baseline. Carbon valuation is based on human-induced (additional) efforts to the baseline and these efforts are defined by a higher magnitude of baseline deforestation then.

Forest-based climate change mitigation may also come by means of improving forest management on managed land by modifying the rotation lengths and intensity of thinning and alike (Golub et al., 2009; Mendelsohn and Dinar, 2009) which would shift F' outward at the intensive margin.

An existing partial equilibrium model, MAgPIE (Lotze-Campen et al., 2008) that employs the implicit land rent approach to agricultural land allocation, is extented to investigate forest-based mitigation options and normative forest conservation in line with the research objectives outlined in Subsection 1.1.2.

1.2.3 Definition of available land for agricultural and forestry expansion

The pressure on land as a required input in competing uses for agriculture and others fuelled research on global land use and the potential for producing food and non-food commodities while conserving biodiversity and carbon sink functions. Thus, trade-offs in land use due to agricultural land expansion to meet food demand are explicitly and implicitly treated in global land use modelling.

Inputs on the initial stock of crop and non-cropland may result from satellite-based biophysical mappings combined with national inventory data (Ramankutty and Foley, 1998; Erb et al., 2007; Klein Goldewijk et al., 2007; Fischer et al., 2002; IMAGE Team, 2001). Several mapping exercises deal with the spatial extent and patterns of global cropland and grassland but lack accounting for non-agricultural land uses (Ramankutty and Foley, 1998; Klein Goldewijk et al., 2007). Extended land mappings are stimulated by the Global Agro-Ecological Zone (GAEZ) methodology on land suitability (Fischer et al., 2002; van Velthuizen, 2007). These exercises exclude land use and cover types (van Velthuizen, 2007) or additionally take population density, proximity parameters and tree cover into account (Bouwman et al., 2006) to allocate land to rainfed crops and pasture according to suitability characteristics. They, however, may still face redundancies in classification. Erb et al. (2007) combine the strength of spatially-explicit mapping and provides consistency with national statistics in land use maps that cover the entire global land stock. The advantage lays in the applicability in non-redundant global land use budgeting.

Global economic and integrated land use modelling approaches as compiled by Heistermann et al. (2006) use rules to define the initial land base obtained from mappings, databases or direct outputs from other models. Exemplifying the economic model class, the land base is set up by regional land type datasets from the World Resources Institute (WRI) (PE AgLU model by Sands and Leimbach (2003)). The weakness of economic models with missing spatial explicitness is the lack of spatial heterogeneity in land endowment. Alternatively, national and subnational statistics on irrigated and rainfed area (PE model IMPACT by Rosegrant et al. (2008)) and rules are applied, *inter alia*, to exclude wilderness (Sands and Leimbach, 2003). In a different approach, spatially explicit available land datasets (IMAGE framework by IMAGE Team (2001)) are defined as regional aggregates in the economic model (CGE GTAP model, Burniaux (2002)).

An example of integrated modelling approaches reveals regional bio-physically-based land classes of the world land stock to set up the stock of allocable land as classes associated with distinct land uses (Geographical Information System (GIS)-based CGE model Future Agricultural Resources Model (FARM) by Darwin et al. (1996)). A different modelling framework (integrated PE KLUM and CGE GTAP model, see Ronneberger et al. (2009a)) sets up the available land based on harvested area per country taken from the United Nations (2005) database. In a third example, the maximum of available land for crop production is derived by excluding protected areas and existing agricultural and urban land and setting up the land base as asymptote of the land supply curve for each region (IMAGE framework and CGE GTAP model, Bouwman et al. (2006)).

1.3 Statement of contribution

The doctoral thesis is designed as monography although a series of publications such as reviewed conference papers linked to Section 2.2 and a published peer-reviewed scientific article in Chapter 3 have been produced already. Chapter 4 has not yet been published. Contributing colleagues coauthored the publications related to the doctoral thesis:

Krause, M.; Lotze-Campen, H.; Popp, A.; Dietrich, J.-P.; Bonsch, M. (2013): Conservation of undisturbed natural forests and economic impacts on agriculture. Land Use Policy. 30(1): 344-354.
Krause, M.; Lotze-Campen, H.; Popp, A. (2009): Spatially-explicit scenarios on global cropland expansion and available forest land in an integrated modelling framework. Selected reviewed paper, 27th International Association of Agricultural Economists Conference in Beijing, China, August 16-22, 2009. IAAE, Milwaukee, USA. AgEcon. 22p. http://purl.umn.edu/51751
Krause, M.; Lotze-Campen, H.; Popp, A. (2009): Global cropland conversion in a spatially-explicit scenario on available land in an integrated modelling framework. Selected reviewed paper. GTAP Twelfth Annual Conference in Santiago, Chile, June 10-12, 2009. GTAP Resource No. 4526. 26p.
https://www.gtap.agecon.purdue.edu/resources/download/4526.pdf

For all chapters I confirm to be the lead author. I was member of the research group 'The Price of Land' at the Potsdam Institute for Climate Impact Research and the doctoral thesis benefited from the contribution of colleagues to different chapters which is listed hereafter.

Chapter 2

The core of Chapter 2 shows the conceptual extensions of MAgPIE implemented in the doctoral thesis. Beside Section 2.1 and Section 2.4, which I have compiled to highlight the key points of conceptual extensions and the mathematical description, Section 2.2 and Section 2.3 have benefited from a number of contributing colleagues from the Lund Potsdam Jena model (LPJ), MAgPIE and Regional Model of Investments and Development (REMIND) modelling communities.

Section 2.2

Together with Hermann Lotze-Campen, I developed the idea and methodology. I collected and processed the data, and prepared the literature overview. I performed the analysis while valuable comments were provided by Hermann Lotze-Campen and Alexander Popp. I prepared scenario applications which were reviewed by the coauthors before presenting them as selected reviewed papers at international conferences.

Section 2.3

Together with Hermann Lotze-Campen I developed the idea of integrating forestry explicitly into MAgPIE. The methodological setup comprised the definition of the growing stock, growth functions and age-class area of global forest vegetation types, which was done by myself, the land allocation mechanism was a joint effort with Hermann Lotze-Campen, Alexander Popp, Jan-Philipp Dietrich, Gunner Luderer, the implementation in the model MAgPIE benefited from comments by Jan-Philipp Dietrich and Isabell Weindl, Susanne Rolinski contributed to the concept of estimating forest commodity demand. Datasets on the growing stock and growth functions of forest vegetation types were derived from Lund Potsdam Jena with managed land model (LPJmL) together with Ursula Heyder and guidance provided by Sibyll Schapphoff and Christoph Mueller. Hermann Lotze-Campen and Christoph Mueller provided valuable feedback throughout the process of implementing forestry into MAgPIE. I gathered other relevant data such as production costs. I developed the input validation methods, performed the coding and quality checks of outputs, wrote the chapter and presented the results.

Chapter 3

This chapter has already been published as a peer-reviewed article and is an application of the consistent land use database and available land estimates from Section 2.2. The idea of analysing the economic impacts of forest conservation was developed together with Hermann Lotze-Campen and Alexander Popp, the specification of scenarios on the prioritization of forest conservation was elaborated by myself. I implemented the scenarios and land allocation mechanism for forest conservation in the model and conducted the optimization runs. Jan-Philipp Dietrich helped on the derivation of land conversion costs. Finally, I wrote the paper, which was thoroughly reviewed and commented by my co-authors.

Chapter 4

Together with Hermann Lotze-Campen, I developed the idea and concept of contrasting options of market-based climate change mitigation in forests and their economic impacts on agriculture and forestry. I developed and implemented the options, namely AD, and AR in conjunction with forest carbon price scenarios in the model. I furthermore performed model runs, the sensitivity analysis and wrote the chapter. My co-authors supported me with helpful comments and a thorough review on the final version of the chapter.

2 Model extensions

2.1 Conceptual extensions

2.1.1 Introduction to the Model of Agricultural Production and its Impact on the Environment

MAgPIE is a spatially-explicit recursive-dynamic global land use optimization model following a nonlinear programming algorithm. In its current state, the partial equilibrium model minimizes the total costs of global agricultural production. It covers the most important agricultural crop and livestock production types in 10 economic regions worldwide and produces economic and bio-physical outputs at a resolution of 0.5 times 0.5 arc degrees taking regional economic conditions and spatially-explicit bio-physical constraints into account (Lotze-Campen et al., 2008; Dietrich, 2011; Dietrich et al., 2012). MAgPIE takes into account the binding constraints, *inter alia* land and water (Lotze-Campen et al., 2008), management intensity and technological change (Dietrich, 2011; Dietrich et al., 2012, 2013). State-of-the-art scenario analyses range from aggregated commodity demand and dietary shifts (Popp et al., 2010) to policy-induced dedicated bioenergy demand over time (Popp et al., 2011), policies on trade liberalization (Schmitz et al., 2011), the impact of taxes on non-CO_2 emissions from livestock and irrigated crop production (Popp et al., 2010), CO_2 emissions from land use change if forest is conserved (Popp et al., 2012) and N_2O emissions from mineral fertilizer or manure use (Bodirsky et al., 2012). From a more disaggregated, sectoral perspective, MAgPIE covers the livestock and agricultural crop sectors including food, feed, fibre and dedicated bioenergy crops. Land use is based on the explicit allocation of existing cropland and pasture land to production activities, and land expansion into a non-specified available land pool in its initial stages (Lotze-Campen et al., 2008). In addition, other land intensive sectors and activities such as forestry or ecosystem conservation are not modelled explicitly. Therefore, there is no comprehensive picture provided neither on the magnitude of land allocation to different sectors, nor the resulting magnitude of land use change and the potential of climate change mitigation including costs.

2.1.2 What is the contribution of the present scientific work? - Land pool database, forestry and extended scenario analysis in MAgPIE

MAgPIE in its current state (Lotze-Campen et al., 2008, 2010a; Popp et al., 2010, 2012, 2011; Schmitz et al., 2011) does not meet the requirements to explicitly model the forestry sector. However, the integration of forestry and agriculture in the land use model enables the analysis of economic, bio-physical and spatial impacts of normative and market-based policies on agriculture and forestry as two land intensive sectors and the trade offs thereof:

- Climate policies in a multi-sectoral context (e.g. taxes on emission-intensive production of agricultural crops, subsidies on AD),

- Sectoral trade policies (e.g. tropical timber trade bans, agricultural commodity trade liberalization, tax of virtual water-intensive commodity trade),
- Sectoral policies on commodity production (e.g. regulations or subsidies on Sustainable Forest Management (SFM), Reduced Impact Logging (RIL) in forestry, rotational constraints and maximum share of irrigated crop production in agriculture),
- Sectoral demand-sided policies (e.g. sales taxes on certain food crops to steer future diets, regulation on the sale of uncertified wood commodities and end products) and
- Ecosystem conservation programmes (e.g. regulations on tropical natural forest conservation)

The development of a spatially-explicit land pool database has been regarded as a prerequisite to perform the analysis of land use trade offs in agricultural and forestry production. The land pool database has already been adopted in several studies (Popp et al., 2010, 2011, 2012; Schmitz et al., 2011). Therefore, the concept and features of two major thematic extensions of MAgPIE, (1) the land pool database and (2) the global forestry sector are explained hereafter (Figure 2.1).

The land pool database is the underlying feature in providing the distinction of land use classes and their non-redundant definition in MAgPIE. It strives to respond to the question addressing the magnitude of physically available land for agricultural and forestry production, forest conservation and plausible land expansion scenarios into unused land. The term 'non-redundant' refers to the strict delineation of land use classes by their dominant use by men even though in reality this is not unambiguous. An example covers the distinction of forested land with its dominant use for wood production, even if browsing by livestock in wood pasture systems may be common as in tropical countries (Gerber, 2010).

The database is consistent by means of each type of land is assigned a type of use and there is no residual land pool. The employment of a non-redundant consistent database of land use pools highlights a human-centered perspective and extends the opportunities of analysing policy scenarios, e.g. by defining which natural forest types are worth being protected in analysing the magnitude of AD and net CO_2 emissions from land use change (Popp et al., 2012).

The definition of spatially-explicit initial forest land pools in a non-redundant consistent way has been the top priority in data integration. This is the prerequisite for the land allocation mechanism as it refines the location and magnitude of managed land expansion, e.g. of cropland which is likely to take place on land more suitable than others but is not covered by managed forests. The concept is lent from Erb et al. (2007) but the database has been disaggregated by detailed forest cover types, land suitability indices, and protected area classes based on remote sensing and statistical datasets (Section 2.2).

The forestry sector ist conceptually based on the minimization of global wood production costs taking spatially-explicit and regional production constraints into account to meet the prescribed derived demand for wood commodities (Section 2.3). Thus, the concept is consistent with the concept of the agriculture sector to ensure the comparability of sectoral outputs. The regional consumption of four wood industries and forestry end products (Subsection 2.3.3)

- Sawnwood, Veneer sheets, Plywood
- Particle board, Fibreboard, Paper and Paperboard

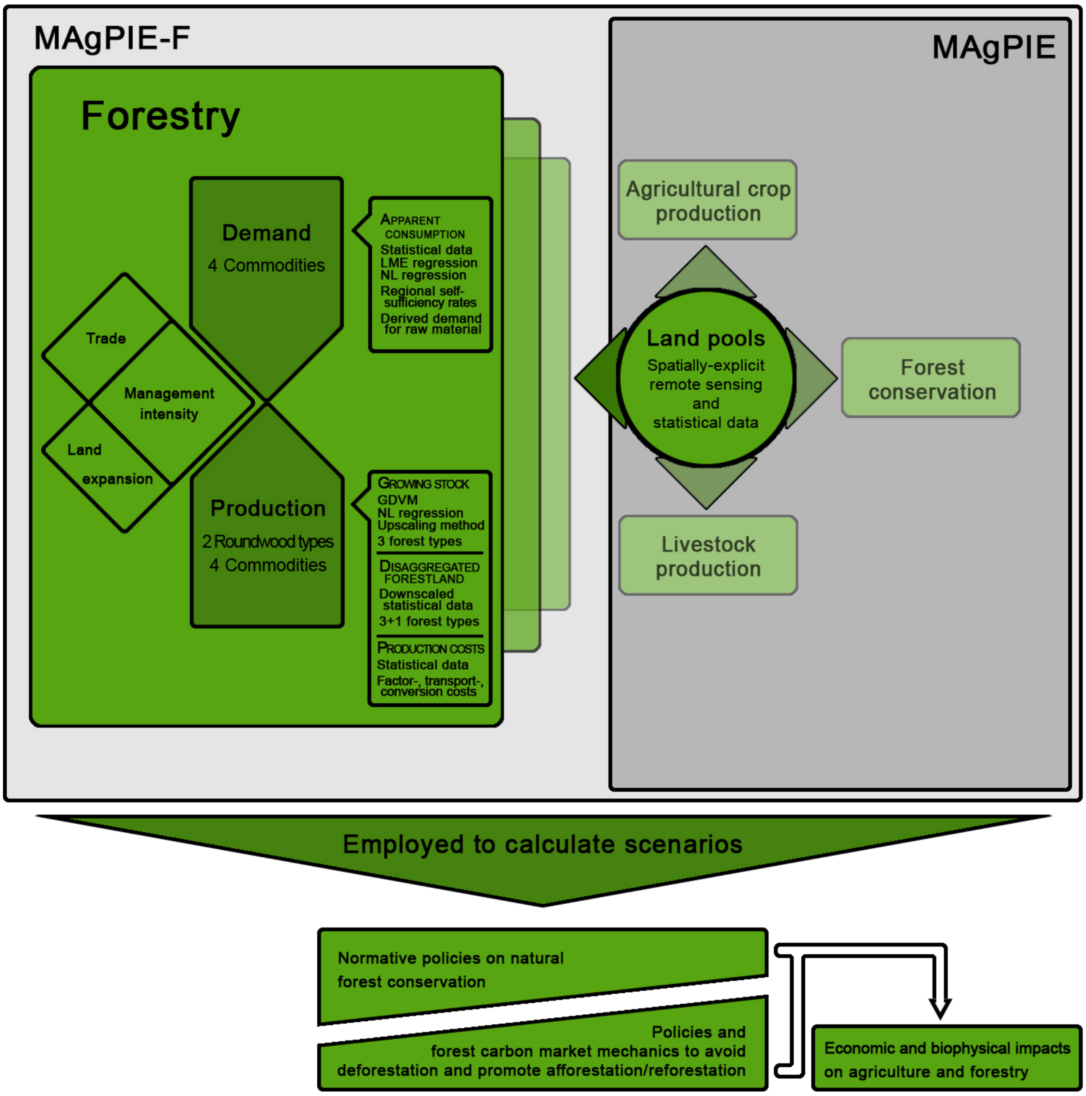

Figure 2.1: Concept of MAgPIE extension by land pool database and forestry

- Other industrial roundwood (End product)
- Woodfuel (End product)

translates into the regional derived demand for four wood raw material (commodities)

- Saw logs and Veneer logs
- Pulp logs
- Other industrial roundwood (Raw material)
- Woodfuel (Raw material)

via statistically-derived shares of self-sufficiency for wood products and wood commodities. Conversion efficiency factors have been used to calculate roundwood equivalent units. The derived demand for raw materials is finally equated to the regional production quantity in roundwood equivalents (Section 2.4). Linear Mixed Effect (LME) regression models for each wood product link the apparent consumption to the independent variable 'Gross Domestic Product (GDP) per capita' and the factor 'Time' to project demand changes into the future and account for time shifts. In the case that LME regression failed, non-linear regression models or plausible assumptions on apparent consumption in the future have been applied.

The production of wood (Subsection 2.3.1) is based on two roundwood types

- Softwood and
- Hardwood

and the associated forest types

- Managed forest (Softwood and hardwood age-class forest),
- Potentially managed forest (Natural forest, 'Other forest' than age-class forest)
- Undisturbed forest (Natural forest).

Production costs accrue for operations such as

- Land conversion (Land clearing and infrastructure),
- Forest establishment (Planting, natural and assisted regeneration),
- Recurrent management operations (Thinning, pruning and other periodically recurrening operations),
- Wood harvest operations and
- Transport to intraregional markets.

The present model version treats wood as a homogeneous good, i.e. each commodity can be produced from each roundwood type. In addition, carbon sequestration and carbon storage functions can be 'produced' in managed and unmanaged forests. The commodity production in each year stems from: a) the merchantable growing stock and its area distribution in forest types generated by means of a Global Dynamic Vegetation Model (GDVM), b) statistical data on forest area and c) the approximation of growing stock from vegetation carbon by biomass conversion and expansion functions. The long-term commodity production for wood supply in the future is approximated by a) the rationally expected derived demand for four wood commodities, b) the future availability of natural forest as source of income and c) an uncertainty surcharge. By this means, future wood supply from managed forests is secured by the corresponding magnitude of forest establishment and management in each year as well as the expected forest growth. A scaling factor in the rate of forest establishment accounts for uncertainties due to other reasons besides future wood demand, such as the expected demand for land conservation and avoided desertification through forests. The decision of planting forests or allocating land to agricultural production is based on the comparison of costs of production expressed as annuity in perpetuity.

The current demand for wood commodities triggers harvest activities according to the local forest productivity whereas the harvest of old-aged forest stands is associated with cost advantages per unit of wood harvested compared to younger forest stands. Wood commodities are produced through various harvest types:

- clearcut of softwood and hardwood age-class forest at varying harvest intensity (rotation lengths),
- clearcut of natural forest and
- selective logging, sustainably in natural forest.

In the current version, the direct conversion of natural forest land to agricultural land does not produce wood products but results in instantaneous carbon emissions. It is argued, that the informal and illegal wood removal, particularly woodfuel removal prior to agricultural land expansion by small-scale farmers, contributes a considerable share to total wood removals but remains unrecorded (FAO, 2006). In addition, the forest area burnt for shifting cultivation is driving deforestation but remains unknown at global scale (Lauk and Erb, 2009). Therefore, official statistics on wood removals are used for calibration of supply which is consistent with the estimatation of regional self-sufficiency rates for wood products (FAO, 2006). For simplicity reasons, the clearing of natural forest for the purpose of age-class forest establishment does does not produce wood products too. This assumption is reasonable, since preceeding natural forest degradation by small-scale loggers or concessionnaires is not covered by the model, but commonly identified as predisposing factor to deforestation in the Tropics (Geist and Lambin, 2002). There are four additional means to bring regional production and demand into equilibrium, through:

- the trade of commodities beyond the self-sufficiency rates,
- a yield-increasing management intensity factor that achieves productivity gains at additional costs,
- varying harvest intensity by clearcutting in age classes and
- clearcutting natural forest area for the purpose of wood production.

Based on the forestry sector and land pool database in MAgPIE, as shown in Figure 2.1, two thematic applications are modelled. The first application deals with normative policies of natural forest conservation in the Tropics and the economic impacts on agriculture (Chapter 3). Second, market-based climate change mitigation programmes in forests exert bio-physical and economic impacts on agriculture and forestry. The sectoral impacts are modelled along with the potential forest carbon supply in the integrated Model of Agriculture and its Impact on the Environment including the Forestry sector (MAgPIE-F)[1] (Chapter 4).

2.2 Setup of a spatially-explicit land pool database

Authors: Michael Krause, Hermann Lotze-Campen, Alexander Popp

[1]Here, the abbreviation 'F' stands for the MAgPIE extension 'Forestry'.

2.2.1 Available land stock in literature

Quantifying the global stock of land, available for different uses by different sectors, is imperative in global supply potential assessments. In agriculture, for global food production to expand the land base is one means to meet demand besides higher productivity and optimized crop rotation. The quantification of land as a scarce primary factor in competing agricultural and non-agricultural human activities has been subject to several studies in the previous decade (Fischer et al., 2002; van Velthuizen, 2007).

From a literature review, mapping exercises have been identified, satellite-based biophysical mappings combined with national inventory data (Ramankutty and Foley, 1999; Erb et al., 2007; Fischer et al., 2002; IMAGE Team, 2001), and databases (FAO, 2006) in connection with rules as the state-of-the-art tool to define initial land pools. The land pool can be set up in various ways, e.g. by regional land type datasets excluding wilderness (Sands and Leimbach, 2003), spatially-explicit total land area excluding protected areas and existing agricultural and urban land (Bouwman et al., 2006), regionally-aggregated bio-physically based land classes using GIS (Darwin et al., 1995), national and subnational statistics on irrigated and rainfed areas (Rosegrant et al., 2008), harvested area statistics (Ronneberger et al., 2009a,b), forest land suitable for crop production by the GAEZ methodology (Fischer et al., 2002; van Velthuizen, 2007), multi-criteria land suitability assessment independent of the GAEZ methodology of the Food and Agriculture Organization of the United Nations (FAO) (Zomer et al., 2008) or abandoned agricultural land for bioenergy use (Campbell et al., 2008).

Empirical climate and soil parameter-based land suitability studies pinpoint 1400 to 2600 million hectares (Fischer et al., 2002; FAO, 2002) and 790 million hectares (Global Land Cover (GLC) 2000) to 1215 million hectares (Moderate Resolution Imaging Spectroradiometer (MODIS)) (Gallagher et al., 2008) to be suitable and has not been used previously for crop production. Available forest suitable as cropland comprises 1170 million hectares (FAO, 2002). About 12 % of the potential land is located in protected areas and 3 % is occupied by human settlements and infrastructure (FAO, 2002). Comparably low estimates are provided by the European Environment Agency ranging from 50 million hectares to 400 million hectares depending on the use of natural grassland (Gallagher et al., 2008).

Erb et al. (2007) stresses the redundancies in classification that may occur through the mix of land use and cover classes and required consistency with national statistics. The advantage lies in the applicability for global land use budgeting.

2.2.2 Elaboration of consistent land pool database, employed datasets and assumptions in MAgPIE-F

Authors: Michael Krause, Hermann Lotze-Campen, Alexander Popp

A hierarchical nested structure is pursued in land data integration following the land use budgeting approach by Erb et al. (2007). Land modules are deliberately combined at different levels to construct area-consistent land inputs into MAgPIE with land use classes (Erb et al., 2007) at the first level, suitable land (Fischer et al., 2002) at the second level, intact and frontier forest (Potapov et al., 2008; Bryant et al., 1997) at the third and International Union for Conservation of Nature (IUCN) areas (UNEP-WCMC, 2004) at the fourth level (Figure 2.2: Panel 1). Third and fourth level datasets have been selected to include land worth being conserved in addition to already protected land for nature conservation. It is assumed that these land areas are associated with high opportunity costs of cropland expansion and the land is not convertible by political consensus. The union of intact and frontier forest comprises about 1.64 billion hectares globally and defines forest worth being conserved in a rather conservative way compared to 1.34 billion hectares of primary forest calculated by FAO (Marklund and Schoene, 2006). By definition, the FAO primary forest category should include intact and frontier forests. The nested data integration is exemplified for the land use type 'Forestry' (Figure 2.2: Panel 2).

Data has been integrated by taking raster-based land use datasets from Erb et al. (2007) at 5 arc minute resolution as a starting point. Datasets on land suitability (denoted by 'SI0' and complementary non-suitable land 'non-SI0'[2]), intact forest and frontier forest (denoted by 'IFFF') and protected area (denoted by 'IUCN') have been converted to raster data in the same projection and entered as boolean data at 5 arc minute resolution. Thus, fractions of land use with particular land suitability have been obtained in each grid cell. The problem of missing values has been overcome by assigning values from neighboring cells based on the Euclidean distance approach. The union of intact and frontier forest has been integrated by rules that are plausible to comprise forest cover and the proportion of allocation to the land use categories. 'Unused' and 'Forestry' land use potentially incorporate intact and frontier forest cover whereas allocation priority has been given to unused land by definition of large intact forest landscapes and frontier forest (Potapov et al., 2008; Bryant et al., 1997). Residual forest cover has been allocated to 'Forestry' land use, which by its wilderness-based distinction from unused forest takes managed and unmanaged natural forest and forest plantations into account (Erb et al., 2007). The remaining forest cover has been capped. Then, protected areas by IUCN have been proportionally allocated to unmanaged forest in forestry, unused and grazing land. In order to avoid redundant and spurious ways of integration, the strictest terrestrial conservation categories I and II are assumed to be covered by the 'Unused', 'Forestry' and 'Grazing' classes owing to the non-presence of nature reserves, wilderness area and national parks in 'Cropland' and 'Urban' areas. At 0.5 arc degree resolution, the consistent cropland dataset has been substituted by a cropland dataset produced by Fader et al. (2010) for the sake of consistency with historical time series. It comprises rainfed and irrigated areas for 13 Crop Functional Types (CFT) and constitutes a synthesis of previous mapping approaches (Portmann et al., 2008; Ramankutty et al., 2008). The proportional allocation of residual land to remaining land use categories has finalized data harmonization. The output consists of global datasets showing land use fractions at 0.5 arc degree resolution, i.e. about 50 km times 50 km at the equator, which is exemplified in Figure 2.3, showing the global distribution of intact and frontier forest and total forest.

[2]The term 'non' expresses the complementary subsets in all other integrated datasets, too.

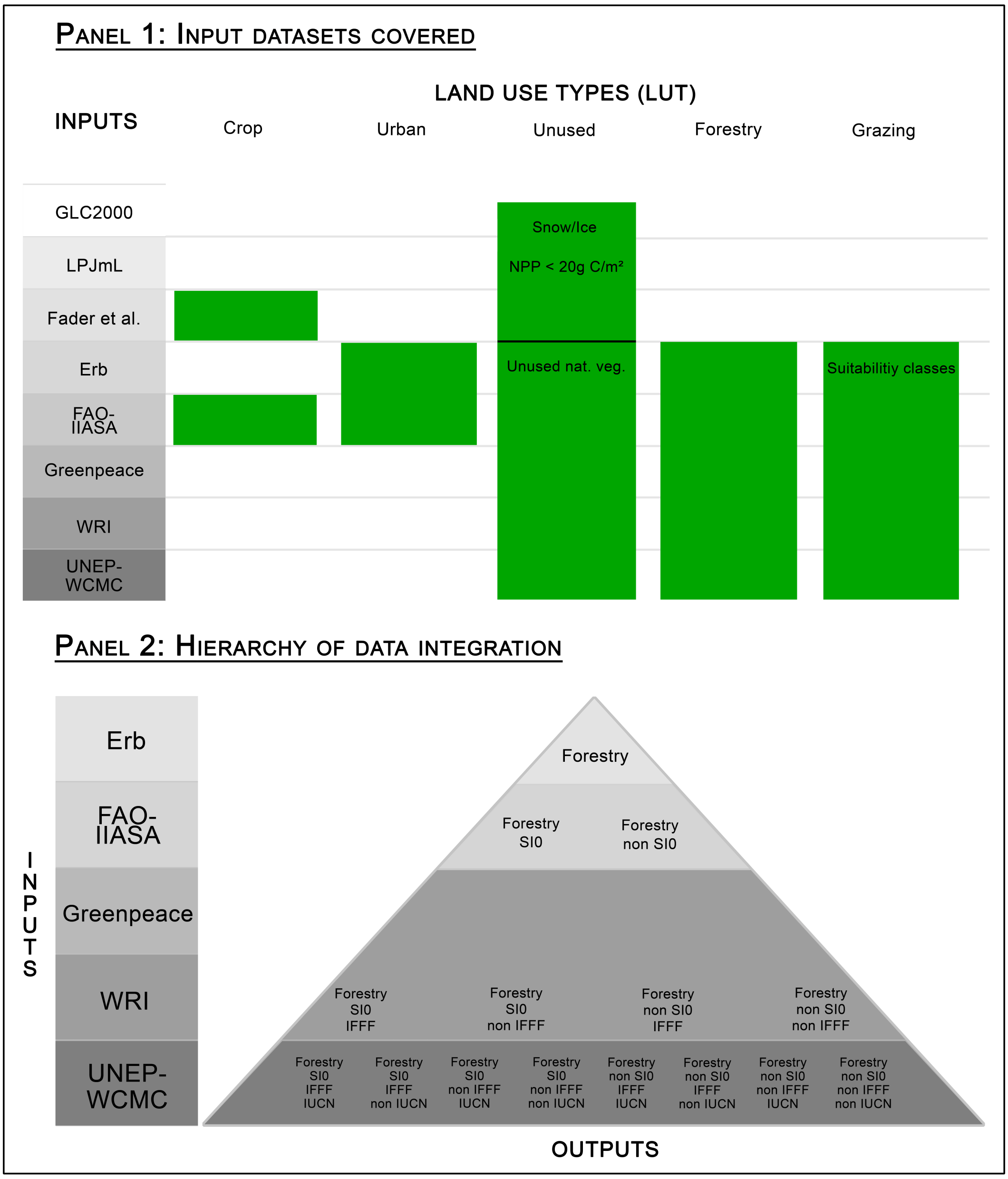

Figure 2.2: Available land modules and scenario groups derived from data integration

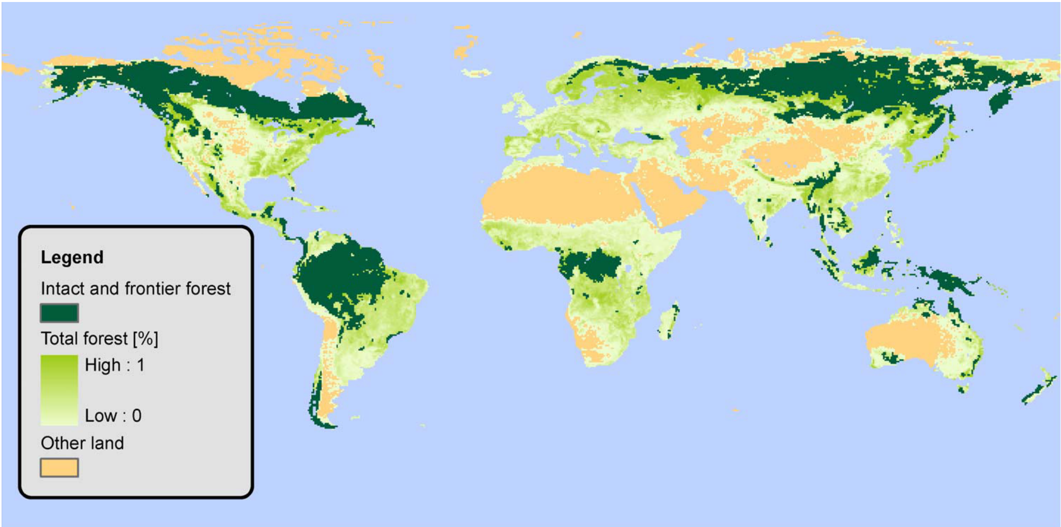

Figure 2.3: Global distribution of intact and frontier forest and total forest

The overview on employed datsets is provided in Appendix B, Table 1.

2.2.3 Data integration for managed and potentially managed forest

Particular attention has been paid to the integration of land covered by forests which is assigned to different uses. Five forest types are distinguished for potential wood supply, age-class forest by wood type, i.e. (I) softwood and (II) hardwood, natural forest subdivided into (III) potentially managed natural forest, denoted as 'Other forest', (IV) pristine 'Undisturbed natural forest' which is accessible through nearby roads, rivers and sea shores, and (V) inaccessible undisturbed natural forest. Undisturbed natural forest is worth being conserved for its ecosystem services, e.g. forest carbon storage and maintenance of biodiversity (Krause et al., 2013) but may also be used for wood extraction. The forest types (I) - (IV) are consistently integrated in 'Forestry' whilst 'Unused' contains forest type (V) (Subsection 2.2.2).

There are two main references available on forest area, age class distribution and growth parameters. The database compiled by Sohngen et al. (2009) and the thematic study on planted forests by FAO (Del Lungo et al., 2006) as addendum to the Global Forest Resources Assessment (FRA) (FAO, 2006). Sohngen's datasets have the advantage of distinguishing forest type areas which make use of FAO datasets and additional country studies and thus provide a more comprehensive picture than FAO has been able to provide[3]. Furthermore, Sohngen et al. (2009) provides economic datasets for different timber management types which have been intended to be used in setting up factor cost. Moreover, Sohngen et al. (2009) allocated forest types to GAEZs (Ramankutty and Foley, 1999) to grasp intra-regional variations. The GAEZ map is based on the length of the growing periods and climatic zones, for more details see Ramankutty and Foley (1999).

However, FAO datasets on plantation and semi-natural forest area (Del Lungo et al., 2006) are useful for defining a managed forest category and the corresponding growth parameters.

[3]Del Lungo et al. (2006) provides a sample of 61 countries, for some parameters with a coverage of 34 countries only

For simplicity, FAO plantations and semi-natural forests are defined as age-class forest only. Sohngen et al. (2009) cover total timberland which is inconsistent by classification with the consistent forest land use database in MAgPIE (Krause et al., 2013). Although semi-natural forest is further subdivided by FAO into regeneration by planting and assisted natural regeneration, it is conservatively assumed that age classes are established on the entire area even if the separation line to other forest management types, likely in e.g. FAO's modified natural forest, is blurred. While Miner (2010) refers to planted forests as the sum of forest plantations and planted semi-natural forests, comprising an area of 271 million hectares, MAgPIE-F purposely covers mainly planted forests and assisted semi-natural forests to define age-class forests with an area of 398 million hectares. The intention is to broadly aggregate FAO forest types according to the predominant mode of harvest. The resulting forest type is defined as managed forest that is actually or potentially age-class forest and clearcut in predefined rotation intervals independent of the provenience of species (I, II). Accordingly, FAO's modified natural forest type is redefined as potentially managed or exploited natural forest that may be selectively logged or clearcut (III) while primary forest covers, per definition, MAgPIE's intact and frontier forest type. The latter may be encroached via selective logging or clearcut (IV, V). In principal, there have been two steps taken in the integration of forest land and particularly age-class forest land (Figure 2.4).

The first step, illustrated by orange-coloured boxes in Figure 2.4, comprises the mapping of distinct timber management types ('MT') summed across age classes and GAEZs (Sohngen et al., 2009) to the plantation and semi-natural forest types ('FT') taken from FAO (2006). The identification of corresponding categories from both references is the backbone of mapping 'MT' to 'FT'. The definitions of 'MT' (Sohngen and Tennity, 2004, p.27ff) helped to assign a preliminary 'FT' identification to each 'MT' including softwood, hardwood, mixed and unspecified plantations and semi-natural forests. The country-level mapping results entered the data calibration to FAO which was accomplished in four stages:

1. The share of each 'MT' at the summed 'MTs' per 'FT' served to proportionally adjust the magnitude of relevant 'MT' to FAO data.

2. The share of each age class in each GAEZ at the summed age classes and GAEZs for each 'MT' was proportionally applied to the FAO-adjusted 'MT' area value per country.

3. The distribution of 'MTs' in corresponding 'FTs' across AEZs was adjusted to the summed spatially-explicit GAEZ area (Ramankutty and Foley, 1999) in MAgPIE's 'Forestry' category per country. This step has been adopted from Sohngen et al. (2009) which served to allocate 'MT' data to GAEZs. By this means, the 'FT' country data is ensured to be consistent with GAEZ areas per country.

4. For cases where the forestry area in MAgPIE was sufficient to integrate the sum of 'FT' area but the other forest area in 'Forestry' (forestry area minus accessible intact and frontier forest) was insufficient, the adjustment of accessible intact and frontier forest area on a country level became necessary. Age-class forest is given priority over accessible intact and frontier forest because the latter dataset has already been conservatively estimated by the union of 1.64 billion hectares and is assumed to be threatened and actually reduced by ongoing deforestation activities. However, the cap of accessible intact and frontier forest

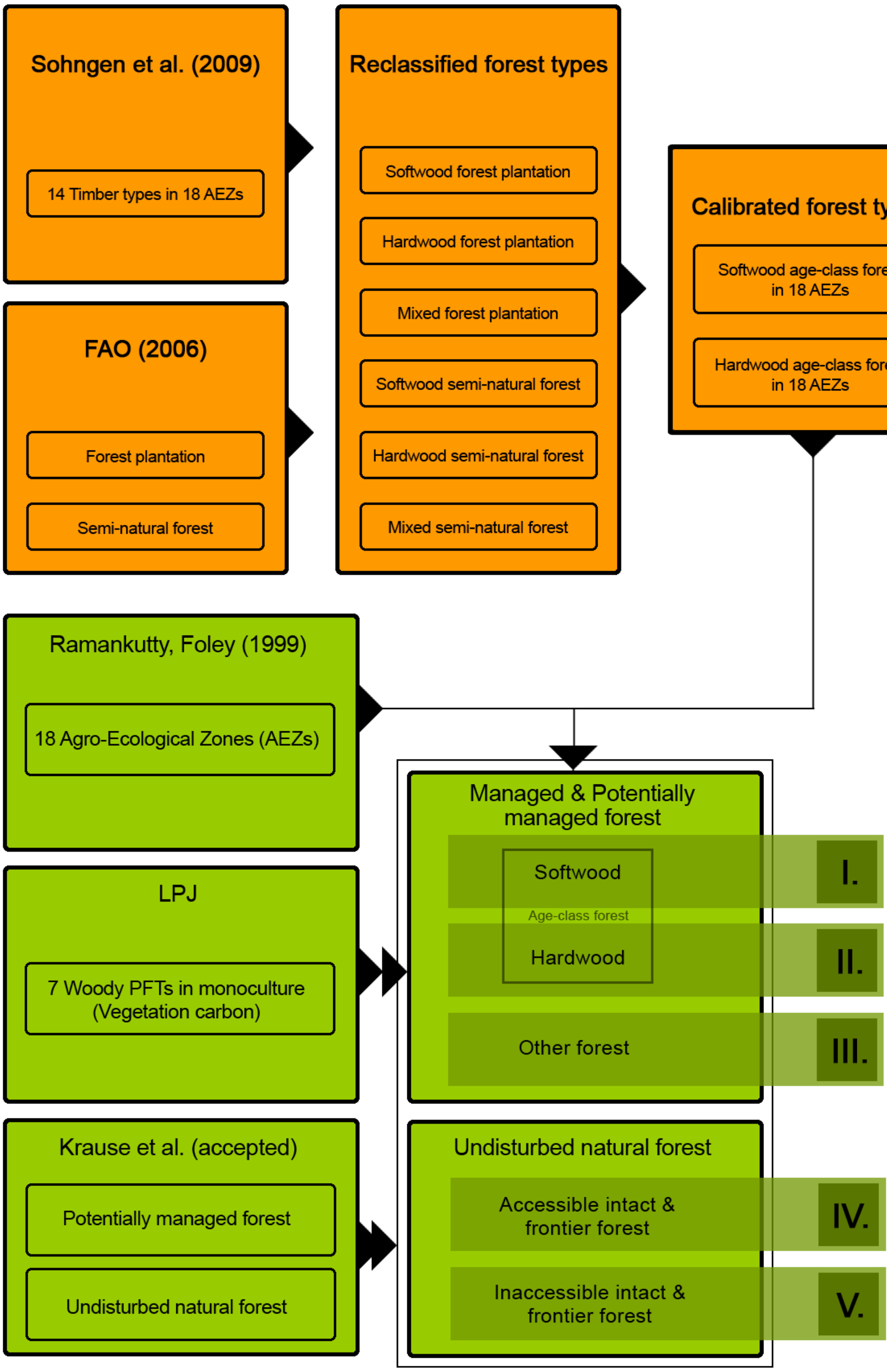

Figure 2.4: Flow chart of deriving forest land datasets and employed references

due to age-class forest data integration adjusts global intact and frontier forests to 1.63 billion hectares, a negligle reduction by 0.7 %.

The number of 'FTs' is finally aggregated to softwood and hardwood forest types because the level of detail on the yield side does not allow a higher degree of disaggregation. This has been done by multiplying the global softwood and hardwood shares at total age-class forest area to the mixed and unspecified age-class forest shares and then taking the sum. The intermediate results comprise age class areas from 10 to 100 years in two FAO-calibrated age-class forest types, softwood and hardwood, in 18 MAgPIE-harmonized GAEZs on a country level.

The sum of softwood and hardwood forest area defines the total age-class forest area. The definition builds on the assumption that semi-natural forests which are the predominant forest types in Europe are managed in a clearcut system with product-specific and forest-specific rotation lengths. The forest area of 398 million hectares was derived to be consistent with MAgPIE's 'Forestry' category (127 million hectares forest plantation and 271 million hectares semi-natural forest)[4]. Furthermore, additional mismatches with summed area of managed and potentially exploited forest in MAgPIE leaves 392 million hectares to be downscaled to grid cells, which is more than 95 % of the original area cover and thus acceptable.

The second step, displayed by green-coloured boxes, deals with the rule-based downscaling of country data to spatially-explicit grid cells at 0.5 arc degree.

1. The map of 18 Agro-Ecological Zones (Ramankutty and Foley, 1999) has been harmonized with MAgPIE's forestry land use category at 0.5 arc degree resolution. Missing GAEZ values at shores (i.e. declared as water in GAEZ map but constituting land in MAgPIE) are removed by adopting non-missing values from the shortest Euclidean distance. The cap of intact and frontier forest area on a country level is proportionally translated across spatially-explicit GAEZs, land suitability and grid cells. Thus, the prerequisite for spatial age-class forest allocation, the consistent country level area of forest types and age classes with GAEZs and MAgPIE's accessible intact and frontier forest is employed from step 1. The age-class forest types and age classes are allocated to grid cells by the proportion of GAEZ area and potentially managed forest area per grid cell at country-level GAEZ area and potentially managed forest area. Consequently, each grid cell per GAEZ shows the same age-class distribution of forest types.

2. The GDVM LPJmL (Sitch et al., 2003) provides maps on the distribution of vegetation carbon for predominant softwood and hardwood forest types. They have been used to refine the allocation of country data to grid cells to avoid area-yield mismatches per grid cell. Such mismatches can occur if the references for area and yield datasets are different, namely if there is a forest area without a yield estimate. The opposite case is possible since potential yields are obtained from LPJmL. Thus, the mismatched softwood and hardwood forest area per GAEZ and grid cell is proportionally re-allocated to grid cells with the same GAEZ but where LPJmL provides potential yields greater zero. The remaining mismatched area is then proportionally re-allocated across all GAEZs.

The spatial distribution of initialized forest types is provided in Figure 2.5, Figure 2.6, and Figure 2.7.

[4]Originally, there are 410 million hectares of forest (139 million hectares forest plantation and 271 million hectares semi-natural forest)(FAO, 2006). However, for several countries there were no data values on matching timber management types and thus age class distribution available.

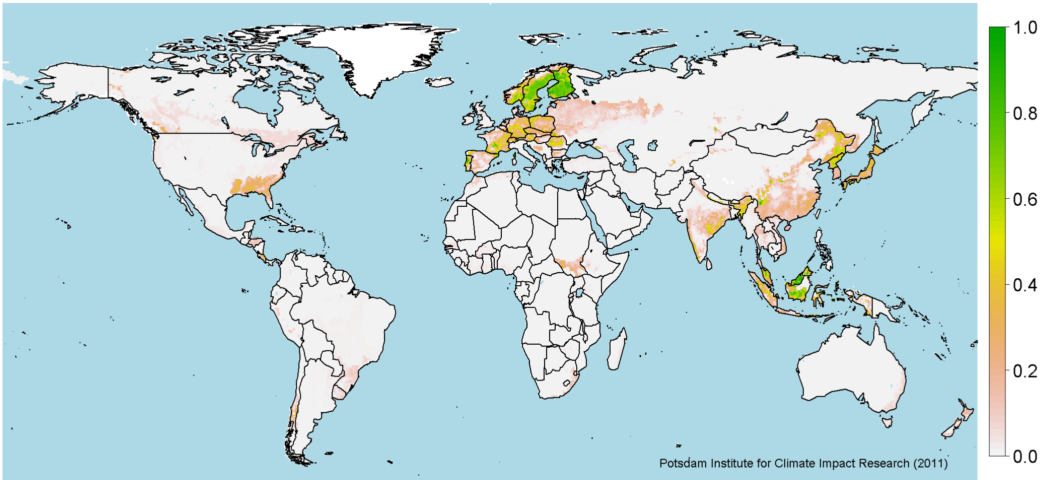

Figure 2.5: Initialized age class forest (Fraction per pixel)

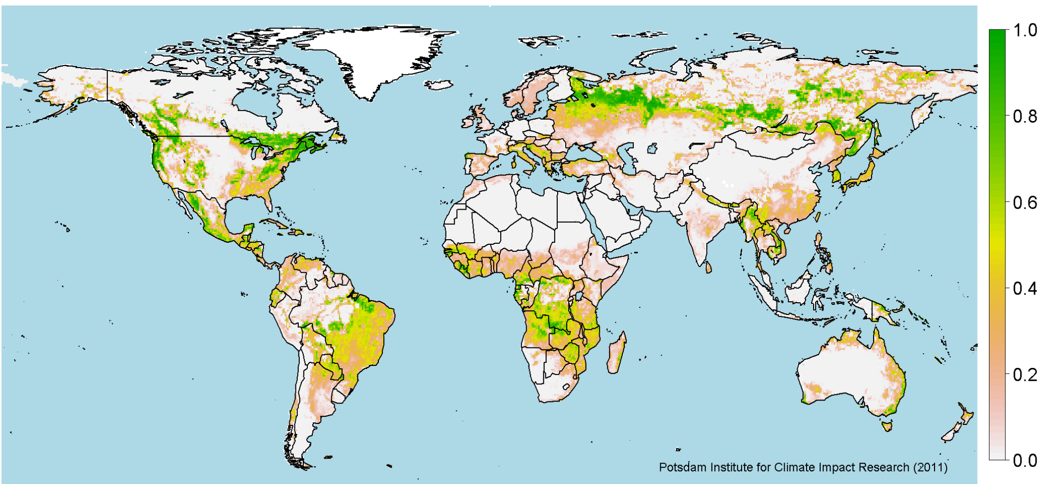

Figure 2.6: Initialized other forest (Fraction per pixel)

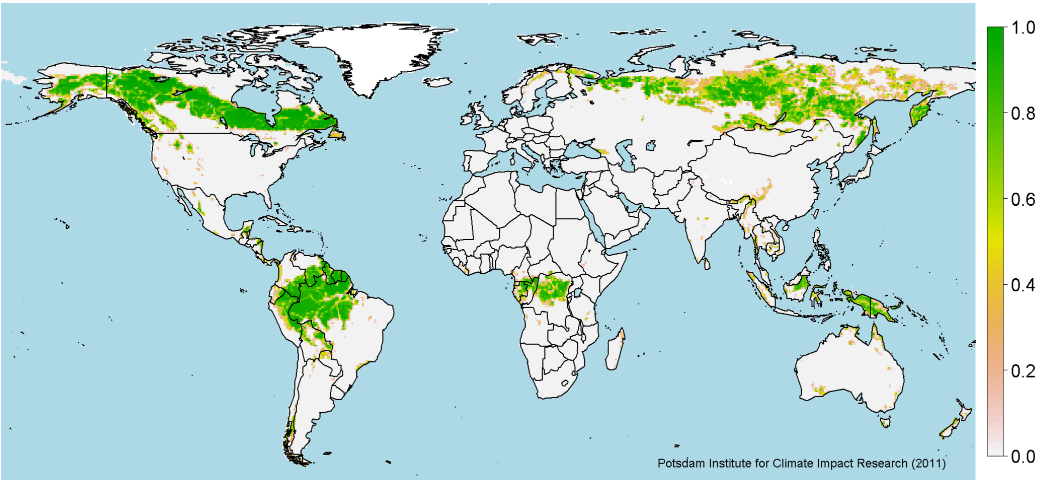

Figure 2.7: Initialized undisturbed natural forest (Fraction per pixel)

The area of forest land pools in distinct forest classes as initialized in the model (Figure 2.4) is contrasted to FAO (2006) (Table 2.1).

Table 2.1: Magnitude of initialized forest area in MAgPIE-F compared to literature (ha)

Region	MAgPIE-F Forest class I: Softwood	II: Hardwood	III: Other forest	IV+V: Undisturbed natural forest	Total	Reference FAO (2005) 1990	2000
	[ha]	[ha]	[ha]	[ha]	[ha]	[ha]	[ha]
GLO	315	77	2093	1624	4108	3958	3864
AFR	13	0	467	109	588	697	644
CPA	62	13	113	19	207	189	206
EUR	85	28	74	3	190	171	176
FSU	21	4	449	448	922	887	894
LAM	13	1	472	510	996	1010	963
MEA	1	0	10	0	11	17	17
NAM	24	10	328	421	783	467	471
PAO	13	1	80	21	114	189	187
PAS	55	11	40	79	185	213	195
SAS	28	9	60	14	111	119	113

GLO = Global, AFR = Sub-Saharan Africa, CPA = Centrally-Planned Asia, EUR = Europe, FSU = Former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS = South Asia

2.3 Setup of the forestry sector

Authors: Michael Krause, Hermann Lotze-Campen, Alexander Popp, Jan Dietrich, Isabell Weindl, Susanne Rolinski, Christoph Mueller, Ursula Heyder, Sibyll Schapphoff, Gunner Luderer

2.3.1 Bio-physical spatially-explicit dimension of wood production

Authors: Michael Krause, Sybill Schaphoff, Ursula Heyder, Hermann Lotze-Campen

Conceptual approach

Authors: Michael Krause, Ursula Heyder

The bio-physical spatially-explicit dimension of roundwood production needs definitions on:

- the productive forest area, area available for forestland expansion,
- growing stocks for the current state in forest types consistent with initialized land pools and aggregated statistical data, and
- forest growth functions for respective forest types.

Subsections 2.2.2 and 2.2.3 have been devoted to the concept of forest area integration and comprehensive explanation of the land pool database. Therefore, the derivation of spatially-explicit growing stocks in age-class forests and other forest types and technical parameters will be introduced hereafter demonstrating the main steps taken.

1. Derivation of vegetation carbon stocks
   Current spatially-explicit vegetation carbon stocks of age-class forest types (Types I and II) are built on current age class distributions and the corresponding carbon stock values per hectare. The per-hectare values are generated by time series for the seven single softwood and hardwood Plant Functional Types (PFTs) by the GDVM LPJ (Sitch et al., 2003). The approach aims at simulating forest growth at predefined climate conditions.

   Other forest types (Types III - V) use forest carbon stocks of average PFTs where woody and grass PFTs directly compete for natural resources. The spin up period brought carbon stocks into equilibrium.

2. Derivation of age-class forest volume growth functions
   Statistical forest growth models were fitted to the time series of forest carbon stocks in PFTs mapped to age-class forest types. Chapman-Richards equations (Mitscherlich, 1919; Richards, 1969) were used to estimate the forest carbon stocks for each spatial unit and PFT under given assumptions on future climate conditions and management.

3. Derivation of biomass expansion and conversion parameter function
   The conversion of vegetation carbon stock to growing stock is based on a non-linear regression model based on year 2005 cross-country data on carbon stocks and growing stocks

from FAO (2006). The dependent variable carbon-to-growing stock ratio is explained by the average growing stock per hectare as an independent variable. The simple model implies a constant average carbon to growing stock relationship across all forest types and management intensity on a global level and skips regional heterogeneity for the sake of simplicity.

4. Conversion of vegetation carbon stock in PFTs to growing stock
   PFTs mapped to hardwood and softwood age-class forest are compared in different time horizons in terms of carbon stocks to determine the most productive, i.e. dominating, PFT of the PFTs in each corresponding age-class forest types. The growing stock in forest types is approximated by forest carbon stocks and historical carbon-to-growing stock ratios as a function of different growing stock levels (FAO, 2006).

5. Calibration of growing stock
   Spatially-explicit growing stocks in age-class forest are proportionally point-calibrated to observed regional growing stocks in planted forests (Del Lungo et al., 2006).

6. Defining harvest levels
   Clearcutting and selective logging are defined as methods of wood harvest. Selective logging is conducted at a sustainable level, which is the net annual increment in the natural forest.

7. Calibration of AR area in age-class forest
   Future wood production partly stems from contemporary AR activities. The calibration of the initial AR rate was done to the observed net change in planted forest area (FAO, 2010) but permitted to diminish over time.

8. Definition of auxiliary parameters
   Additional parameters define the historical and projected roundwood production share from age-class forests and restrict the per-grid cell AR area (barrier- to- implementation parameter for forest established for carbon sequestration).

Step 1: Derivation of vegetation carbon stocks

Authors: Michael Krause, Sybill Schaphoff, Ursula Heyder

The starting point for estimating the growing stock in forest types is set by using an existing version of the LPJ model (Sitch et al., 2003) to generate spatially-explicit global patterns of potential vegetation carbon in seven PFTs at a resolution of 0.5 arc degree. The LPJ model has been used in several applications to generate patterns of so-called average individuum of PFTs which expresses the growth of boreal, temperate and tropical softwood and hardwood forests and C3 and C4 grasses per hectare. The simulation of carbon stock densities and vegetation carbon change dynamics commonly start with the equilibrium of regrowth and mortality after a predefined spin-up phase. Previous studies cover the change under natural hazards like fire (Thonicke et al., 2001) or the change in athmospheric CO_2 concentration levels due to climate change (Schaphoff et al., 2006) and deforestation (Gumpenberger et al., 2010; Cramer et al., 2004).

On the one hand, the current study needs LPJ to generate output on the vegetation carbon pool for natural forest (forest types III to V, Figure 2.4). Therefore, the standard LPJ model is applied based on the average individuum approach where woody and grass PFTs directly compete for natural resources. A spin-up period of 1000 years was defined to bring carbon pools in 9 PFTs into equilibrium. The model generated outputs on the vegetation carbon forced by an atmospheric CO_2 concentration of 450 ppm and recycled climate data from 1974 to 2003, compiled by the Climatic Research Unit (Mitchell et al., 2004), into the future for 200 years. Three simulation runs have been made to eliminate historical random weather (precipitation) effects. The precipitation was held constant into the future, therefore the impact of precipitation changes on spatial patterns is neglected. River routing and fire have been disabled.

On the other hand, outputs for the growth of age-class forest types (forest types I and II, Figure 2.4) are required which is reflected by vegetation carbon accumulation over time but not an equilibrium state of carbon across different pools. The LPJ model underwent modifications regarding the initialization of single PFTs instead of all PFTs at once and the write-out of outputs without initial spin-up. The photosynthetic assimilation rate at leaf level is scaled to the ecosystem level via the *alphaa* parameter (Fader et al., 2010) which is intuitively changed from 0.5 for all PFTs to a value of 0.8 for separately grown PFTs. This parameter covers the entire range of possible threats to the successful biomass accumulation in PFTs like self-shading among the PFTs which grow in mixed stands as well as biotic and abiotic damaging events. It is assumed that age-class forest management and the planting arrangement of trees is optimized. Silviculture and forest protection measures take place and stands are less browsed and trampled by game and livestock to reduce the negative impact on biomass growth. Appendix B, Figure 1 shows the spatial distribution of the potential vegetation carbon in PFTs.

The outputs generated by the LPJ model comprise time series datasets on projected vegetation carbon of seven separately grown woody PFTs for 200 years from 2003 onwards with a spatial resolution of 0.5 arc degree (Figure 1). The calculated arithmetic mean of the vegetation carbon datasets for each of the PFTs entered the estimation of growth functions for age-class forest types I and II. The vegetation carbon of PFTs grown under competition ('PFT MIXED') was averaged for 1994 to 1996 to proceed with the derivation of the growing stock in natural forest types III to V.

Step 2: Derivation of age-class forest volume growth functions

The time series datasets on mean vegetation carbon for separate woody PFTs have been fitted to a Chapman-Richards growth function (2.1) (Mitscherlich, 1919; Richards, 1969; Zeide, 1993). This function is commonly used in forestry for its flexibility to model the nonlinear volume growth of trees in stands (Cooper, 1983; Venn et al., 2001; Cacho et al., 2003).

$$y = par.a(1 - e^{-par.b\ x})^{par.c} \tag{2.1}$$

The parameter *par.a* determines the asymptote for growth which constitutes the equilibrium state of mortality and regeneration on a stand level per hectare under the assumption that natural damaging events are negligible and coped with by optimum management. The parameters *par.b* and *par.c* shift the slope and shape of the function along the x-axis. Human interference is assumed to be the only driver of changes in carbon stocks.

In a two-stage fitting procedure, the first stage comprised the application of a relatively imprecise but robust optimization algorithm to 'pre-fit' the time-series data[5]. The initial parameter

[5]Before the 'pre-fit' has been conducted, the datasets had been pre-processed. Only grid cells with continuous

values were arbitrarily selected. The function was then rearranged to locally minimize the sum of the squared residuals over the vector of parameters (2.2).

$$\text{minimize} \sum \left(y - (par.a(1 - e^{-par.b\ x})^{par.c})\right)^2 \tag{2.2}$$

The intermediate output, the optimal combination of parameter values, was used at the second level of fitting procedure using a more precise algorithm[6].

Chapman-Richards growth models with the estimated vegetation carbon stock $y = \widehat{CS}$ in woody PFTs as function of time $x = t, t \in T$ constitute the output of Step 2.

Step 3: Derivation of biomass expansion and conversion parameter function

The forest carbon in tons per hectare from LPJ is converted to growing stock in m^3 per hectare as a prerequisite for gauging the volume of parts of stemwood and / or branches that are available for roundwood removal. A Biomass Expansion Factor (BEF) commonly links aboveground biomass to biomass of the growing stock in tons of dry matter (Marklund and Schoene, 2006). Small branches, twigs, foliage, flowers, seeds, and roots are excluded but windfallen living trees may be included in BEFs (Marklund and Schoene, 2006). A Biomass Conversion and Expansion Factor (BCEF) incorporates the conversion of biomass in tons of dry matter to m^3 of fresh matter over bark (Marklund and Schoene, 2006, p.20f). For more details on a broader range of BEFs and BCEFs application, see Eggleston (2006).

Hereafter, the conversion of volume growing stock to carbon stocks in tons per hectare is defined as BCEF which bases on the ratio of 'Carbon in aboveground biomass', CS^{AB}, in forests (FAO, 2006, Tab.14) and the 'Total growing stock in forest', GS, (FAO, 2006, Tab.11) in per-country k datasets (2.3).

$$BCEF_k = \frac{CS_k^{AB}}{GS_k},\ \forall\ k \in K \tag{2.3}$$

China serves as an example of the derivation of the BCEF from carbon (tons) to growing stock (m^3). The total carbon stock of 4636 million tons carbon refers to aboveground biomass while the total growing stock is 13255 million m^3. Assuming an average carbon density of 0.5 tons of carbon per ton of dry matter biomass and an average wood density of 0.5 tons of dry matter per m^3 of growing stock, the equivalent biomass stock of carbon would be 9272 million tons of dry matter compared to 6628 million tons of dry matter from the growing stock. There is a difference

vegetation carbon time series were selected to warrant efficient function optimization. All those grid cells were excluded from the pre-fit where the vegetation carbon values in the year 200 decreased by 50 % compared to the maximum vegetation carbon value for each of the PFTs. In such grid cells the vegetation carbon time series is considered to not be robust. Furthermore, the first 8 years of time series data have been discarded due to the implementation of the establishment of PFTs and area allocation in LPJ. In the last step in pre-processing the grid cells were removed that did not show a vegetation carbon stock greater zero at the age of 1 or 10. 'Pre-fitting' was done by means of the Broyden-Fletcher-Goldfarb-Shanno (BFGS) quasi-Newton method (Nocedal and Wright, 1999), which has been employed to find the stationary point of the function to be fitted to. The first level in fitting used the R statistical software and the L-BFGS-B method provided by the 'optim' function of the 'stats' package. Each variable, here parameter value to be identified, can be given a lower and/or upper bound (Byrd et al., 1995). It works in the way that initial boundary values for the parameters to be optimized over and a function are defined first.

[6]The function 'nls' of the R package 'stats' was employed.

of 2644 million tons DM which is the residual portion of the aboveground biomass not defined as growing stock, e.g. branches, aboveground part of stumps, twigs and leaves. However, skipping the conversion step of growing stock to biomass has an advantage. The carbon-to-growing stock conversion factor implicitly takes the country-specific definitions of wood density and carbon contents into account, which do not need to be prescribed in MAgPIE-F.

The functional relationship between growing stock and observed BCEF based on country-level datasets is shown in Figure 2.8.

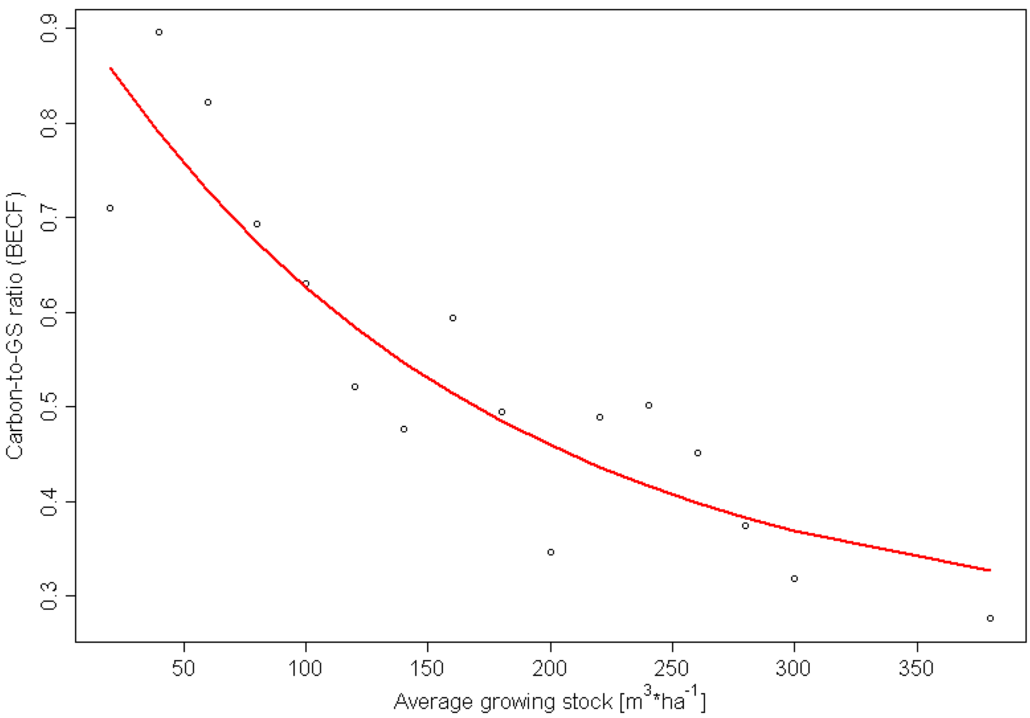

Figure 2.8: Global average BCEF function

The decreasing exponential function has been intuitively selected. It shows a sufficient model fit (R^2: 0.81) to estimate $\widehat{BCEF}$ for data intervals with a step-width of 20 m^3 from the average growing stock 'GS' as independent variable, see Equation (2.4).

$$\widehat{BCEF}(GS_k) = 0.674\ e^{-0.0062\ GS_k} + 0.2629,\ \forall\ k \in K \tag{2.4}$$

The result across different forest types pinpoints the positive correlation of growing stock and share of biomass, not defined as growing stock, which increases with smaller carbon-to-growing stock ratios. Marklund and Schoene (2006, p.21, Fig.5.1) evidence that the BCEFs decrease with increasing growing stock from case studies for norway spruce forest, temperate broadleaved forest, and tropical broadleaved forest accordingly. But, the BCEF is also determined by the tree species grown, the forest structure and stem distribution across diameter classes (Marklund and Schoene, 2006), which is not grasped hereafter. Eggleston (2006, Tab.4.5) confirm that lower values for BCEF apply 'if growing stock definition includes branches, stem tops and cull trees', whereas upper values 'apply if branches and tops are not part of growing stock, minimum top diameters in the definition of growing stock are large, inventoried volume falls near the lower category limit or basic wood densities are relatively high'.

The output of Step 3 is a BCEF function $\widehat{BCEF}(GS)$ which is required to convert vegetation carbon stocks to growing stock.

Step 4: Conversion of vegetation carbon stock in PFTs to growing stock

The next step requires the outputs of the Chapman-Richards forest carbon growth models (outputs of Step 1 and Step 2 for forest types I and II) and the equilibrium vegetation carbon stock in natural forest (forest types III to V) to infer the aboveground biomass part of woody vegetation. The estimated aboveground forest carbon stock is denoted as $\widehat{CS}^{AB}$. The link was established by means of a root-to-shoot ratio of belowground to aboveground biomass RS of 0.3 which is within the range of ratios employed for tropical forests (Deans et al., 1996; Doherty et al., 2010) and boreal forests (De Deyn et al., 2008) and the compilation by IPCC (Penman et al., 2003).

$$\widehat{CS}^{AB} = \widehat{CS}\ (1 - RS) \tag{2.5}$$

The estimated aboveground forest carbon stock and the estimated biomass conversion and expansion factors (output of Step 3) were used for the approximation of the growing stock. The solution is not straightforward since the estimated aboveground biomass and respective carbon stock is a function of the estimated biomass conversion and expansion factor $\widehat{BCEF}$ and the observed growing stock GS (Marklund and Schoene, 2006), however a solution of the equation for GS is needed. Since the solution of the equation for GS as the dependent variable is analytically infeasible, a numerical iteration approach has been pursued. In Equation (2.6), the hypothetical carbon stock of aboveground biomass $\widetilde{CS}^{AB}$ has been calculated by means of a hypothetical growing stock $\widetilde{GS}$ and the estimated biomass conversion and expansion factor $\widehat{BCEF}$ as a function of the observed growing stock GS (see equation (2.4)). The ordered values $g \in G$ of the hypothetical growing stock $\widetilde{GS}$ are intuitively set to a precision level of $2 * 10^{-2}$ with $\widetilde{GS}_{1..G}\,\{0, 0.02, 0.04, ..., 1200\}$.

$$\widetilde{CS}^{AB}_g = \widetilde{GS}_g\ \widehat{BCEF}_g(GS),\ \forall\ g \in G \tag{2.6}$$

The estimated aboveground forest carbon stock values from LPJ, $\widehat{CS}^{AB}$, are adapted to the precision level in $\widetilde{CS}^{AB}$ to ensure matching values and derive the estimated growing stock $\widehat{GS}$ from the hypothetical growing stock $\widetilde{GS}$. The approximation rule

$$\widehat{GS} = \widetilde{GS} : \widehat{CS}^{AB} = \widetilde{CS}^{AB} \tag{2.7}$$

has been applied to estimate the growing stock $\widehat{GS}$ in single and mixed PFTs (forest types I to V). PFTs are mapped to forest types as shown in Table 2.2.

Softwood and hardwood PFTs are used to define the growing stock in forest types I and II. Spatial overlaps have been revealed at the edges of the potential distribution of PFTs based on plant physiological responses to climate and site variables. The overlaps amount to 71 % and

Table 2.2: PFTs mapped to forest types

Forest type	Acronym of PFT	Full name of PFT
I: Hardwood	PFT1	Tropical broadleaved evergreen tree
	PFT2	Tropical broadleaved raingreen tree
	PFT4	Temperate broadleaved evergreen tree
	PFT5	Temperate broadleaved summergreen tree
	PFT7	Boreal broadleaved summergreen tree
II: Softwood	PFT3	Temperate needleleaved evergreen tree
	PFT6	Boreal needleleaved evergreen tree
III-V: Natural	PFT MIXED	Natural forest vegetation

1.3 % of the total number of grid cells with carbon stock greater zero in PFTs corresponding to forest types I and II respectively. It is assumed that the dominating PFT in each of the forest types I and II are grown in that case. The dominance of PFTs is defined by the highest Mean Annual Increment (MAI) over years t with $t \in T\{1,...,110\}$ indicating superior total growth performance. T denotes the average rotation age of stands for growing timber in Europe and the Former Soviet Union (Del Lungo et al., 2006, Tab.6a).

Step 5: Calibration of growing stock

The spatially-explicit age-depending growing stocks in age-class forest types have been point-calibrated to regionally observed mean growing stocks in planted forest (Figure 2.9). The reference values have been taken from the thematic study on planted forests by FAO (Del Lungo et al., 2006)[7] and have been aggregated to regional values by production-area weighted mean[8]. Point calibration refers to the growing stock at a specific forest age after an observed average minimum rotation length has been reached. The rotation length is determined by the wood production cycle from regeneration to harvest by terminal cut. Step 4 provides the estimated growing stock $\widehat{GS}$ over years $t \in T$ in grid cells $j_i \in J_I$ per region $i \in I$ for each age-class forest type. $\widehat{GS}$ has been adjusted to the calibrated growing stock $\overline{GS}$ by the calibration factor ω at a specific rotation length RL.

$$\overline{GS}_{t,j_i} = \widehat{GS}_{t,j_i}\omega_i, \ \forall \ j_i \in J_I, \ for \ t = RL \tag{2.8}$$

whereas

[7] Forest production parameters are provided like MAI and rotation length by minimum and maximum values from several case studies covering 61 countries globally.

[8] More refined data would have been available for Europe and Russia by the United Nations Economic Commission for Europe (UNECE) European Forest sector outlook study (FAO and UNECE, 2005) and databases on growth performance of different temperate and boreal forest types. However, global consistent datasets are not available (only provided as model output in the global timber model database by Sohngen et al. (2009)), which has been reason to adopt FAO values.

$$\omega_i = \frac{\sum_{k_i=1}^{K_I}\left(GS_{t,k_i}A_{k_i}\right)}{\sum_{k_i=1}^{K_I}A_{k_i}} \Big/ \frac{\sum_{j_i=1}^{J_I}\left(\widehat{GS}_{t,j_i}\widehat{A}_{j_i}\right)}{\sum_{j_i=1}^{J_I}\widehat{A}_{j_i}} \; for\ t = RL \tag{2.9}$$

defines the ratio of the area-weighted observed and estimated mean growing stocks per region with $k_i \in K_I$ indexing the countries mapped to regions, GS denoting the observed growing stock (Marklund and Schoene, 2006) at the minimum rotation length RL, A and $\widehat{A}$ the observed and estimated forest areas.

The remaining growth function values have been adjusted by the percentage change of estimated-to-calibrated growing stock at the minimum rotation length to maintain the shape of the growth functions.

The observed minimum rotation length is commonly based on:

- a biological criterion, the point in time when the Current Annual Increment (CAI) intersects with the MAI, i.e. the slope of the MAI is zero (e.g. valid for relatively short rotation lengths with 10 - 40 years for woodfuel, pulpwood and poles production),
- the financially optimal rotation length defined by the Net Present Value (NPV) of the expected revenue and cost stream in the future from timber stands (e.g. in tropical plantations),
- quality requirements for certain wood assortments (e.g. minimum diameter dimensions required for timber assortments and rotation ages > 100 years),

or a combination thereof. However, the criteria used in practice deviate from advanced economic approaches on the optimum rotation length[9] by either not considering the opportunity costs of current wood production (biological criterion) or not including the value of land in opportunity cost calculation (NPV criterion).

In addition to the point calibration of growing stocks in age-class forest, the maximum obtainable values at the age of 110 years are capped to remove outliers at 1000 m^3. This value constitutes a conservative estimate compared to literature where the maximum harvested volume data for planted forests in 61 countries are compiled to exceed 1000 m^3 at an even shorter rotation length (Del Lungo et al., 2006). Del Lungo et al. (2006) provides examples for softwood plantations in Europe (*Picea abies*, 70 years, 1300 m^3, Great Britain) or hardwood plantations in Latin America (*Araucaria angustifolia*, 35 years, 1050 m^3, Brazil). It is assumed that the maximum harvested volume may serve as a proxy for the growing stock.

The estimated growing stock of global forests, i.e. age-class forest, other forest and undisturbed natural forest is presented hereafter in Figures 2.10, 2.11, and 2.12.

The figures 2.10 and 2.11 show the first quartile, median and third quartile of calibrated regional growing stock values over time.

Figure 2.12 displays standard boxplots showing minimum, first quartile, median, third quartile, and maximum values of estimated regional growing stocks. Outliers are indicated by dots.

The figures compare well to FAO growing stock data for 2005 at the global scale (Marklund and Schoene, 2006; FAO, 2006). The area-weighted average growing stock in age-class forest

[9]See Subsection 1.2.1 for references to the LEV and its application in forest economics and timber land allocation.

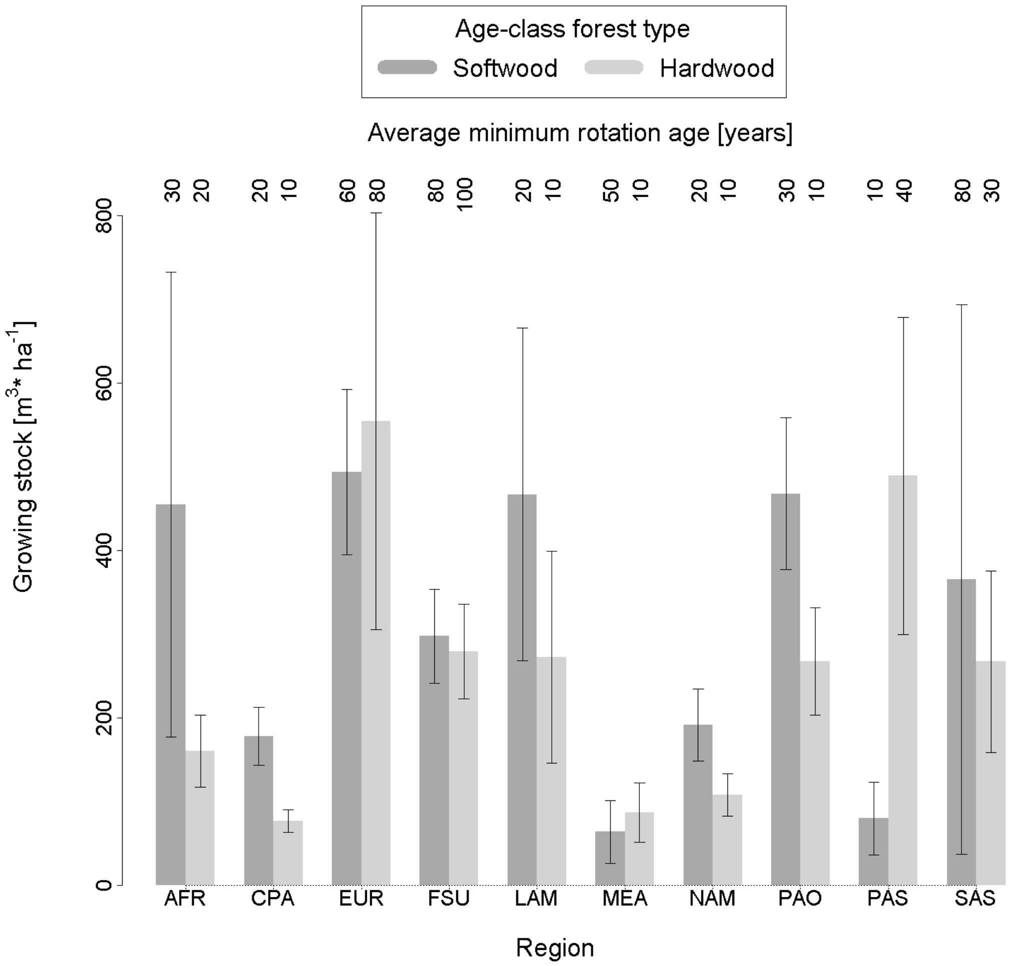

Figure 2.9: Mean growing stock (bars in figure) and standard deviation (range in figure) of age-class forest at minimum rotation length calibrated to FAO

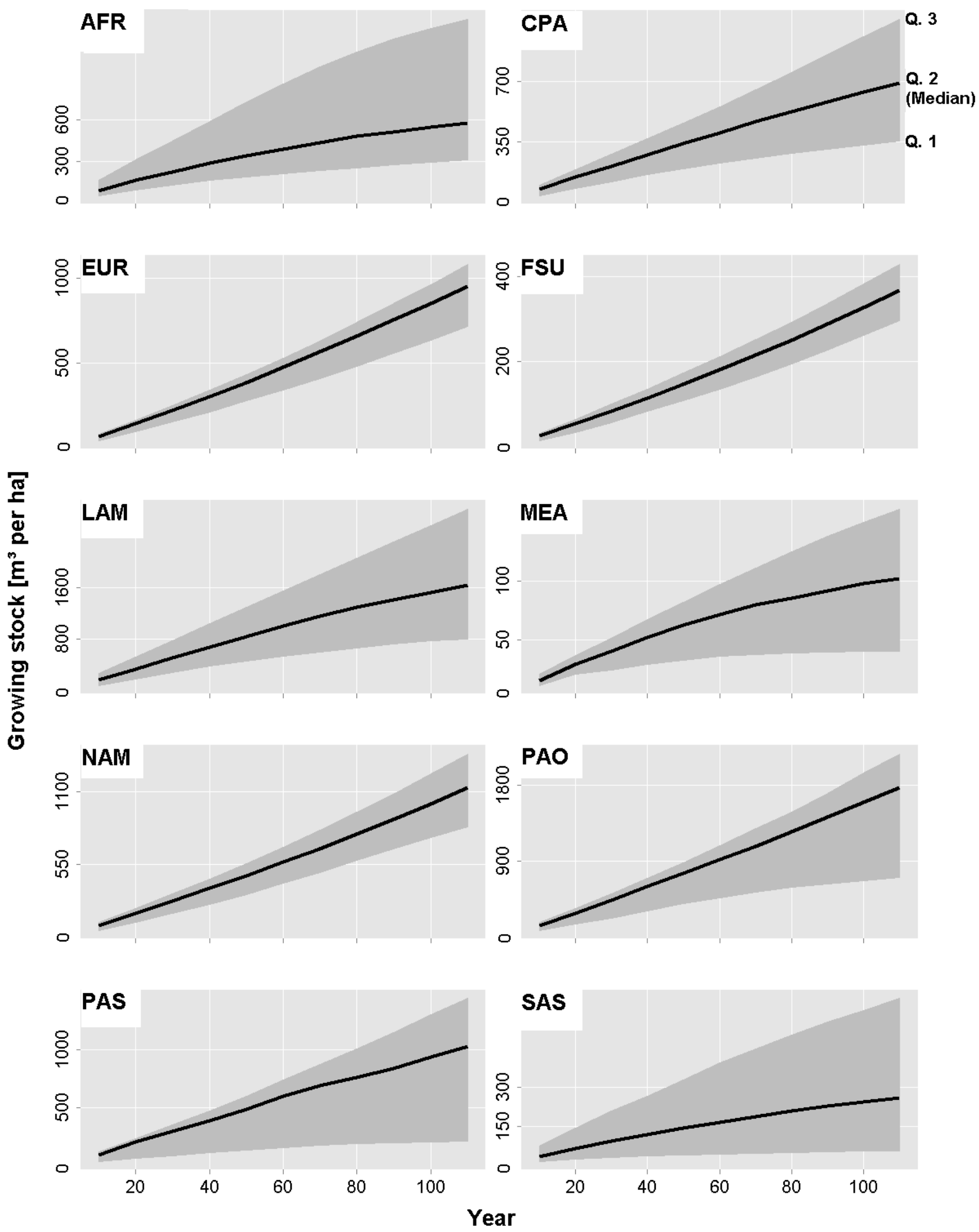

Figure 2.10: Calibrated growing stock in softwood age-class forest (forest type I) over time. The upper bound of wedges shows the 75th percentile, the black line indicates the median and the lower bound grasps the 25th percentile.

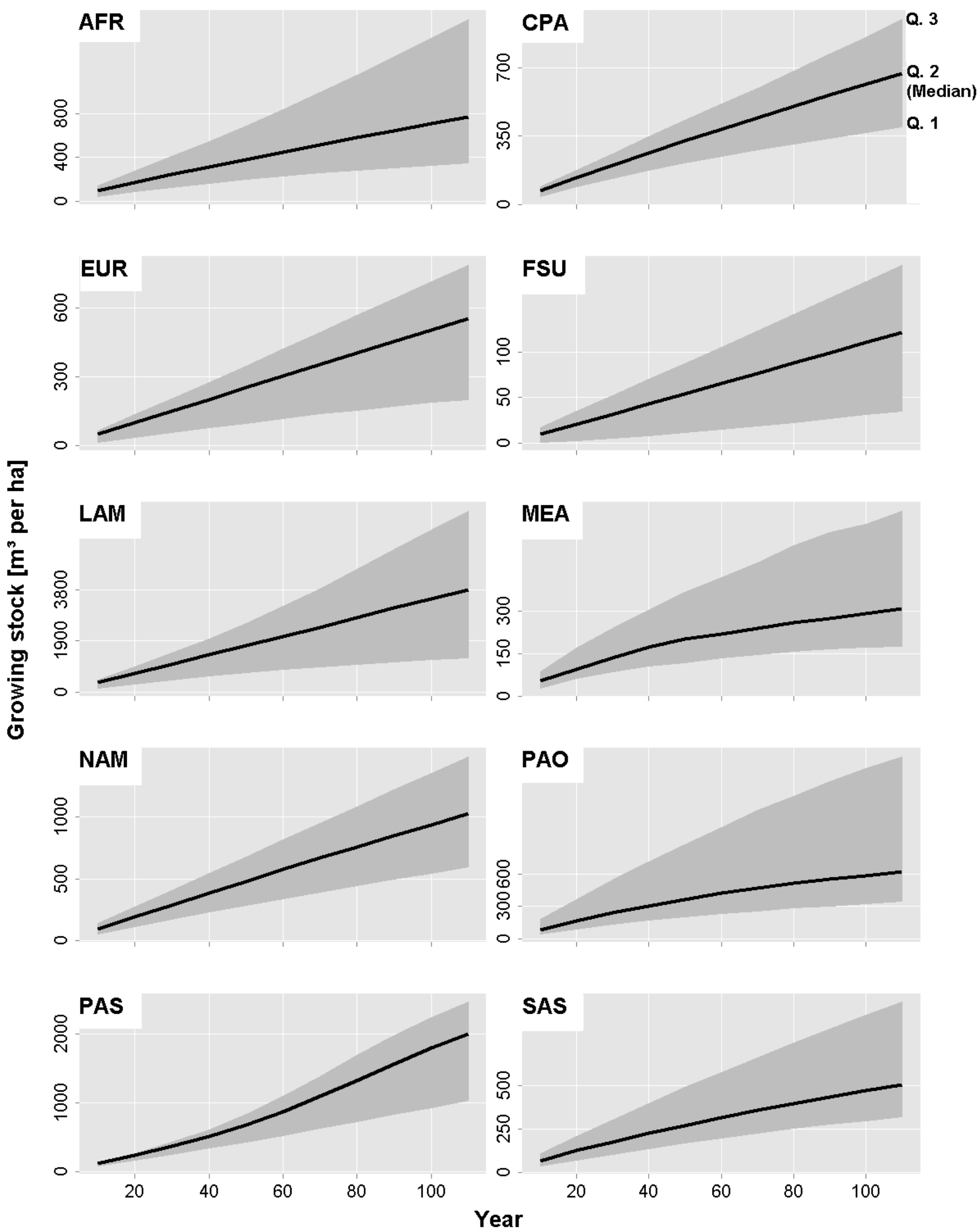

Figure 2.11: Calibrated growing stock in hardwood age-class forest (forest type II) over time. The upper bound of wedges shows the 75th percentile, the black line indicates the median and the lower bound grasps the 25th percentile.

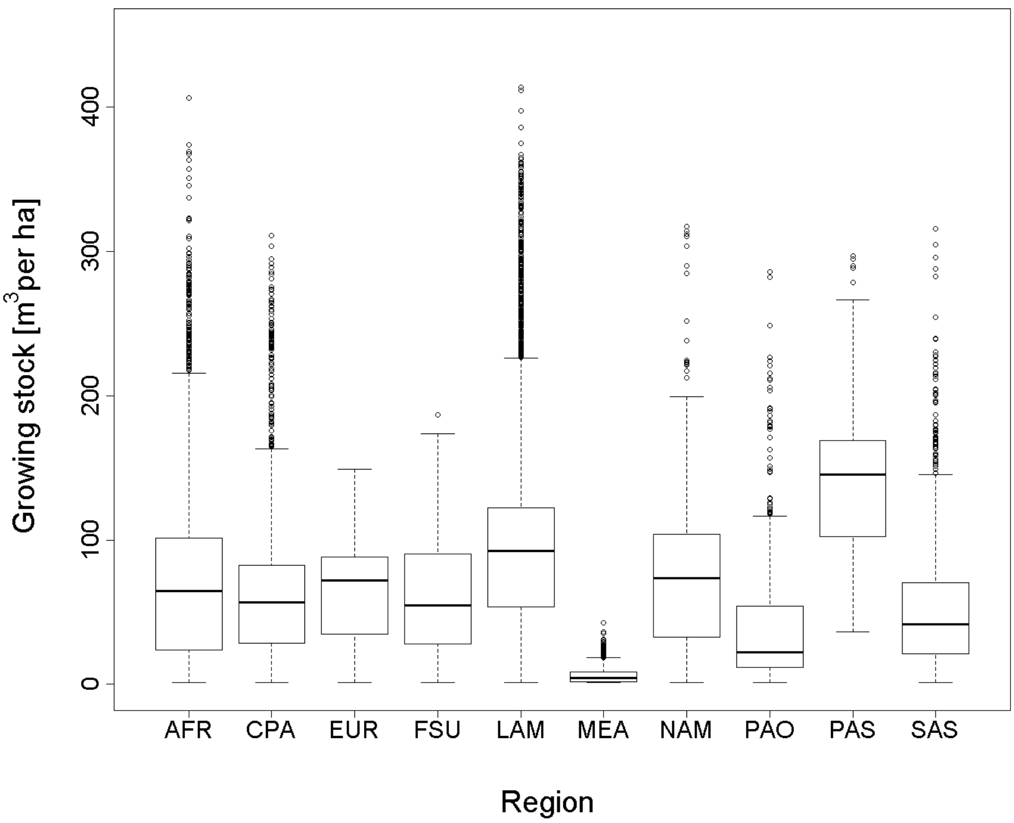

Figure 2.12: Estimated equilibrium growing stock in natural forest (forest types III to V). The boxplots display the median (black line), the upper and lower quartile (box), the minimum and maximum of the distribution (whiskers), and the outlier (dots).

(forest types I and II) amounts to 294 m^3 dry matter per hectare and 90 m^3 dry matter per hectare in natural forest (forest types III to V) globally. If taken as a total area-weighted average value, the growing stock of 108 m^3 dry matter per hectare matches well with the 110 m^3 dry matter per hectare provided by FAO (2006).

Step 6: Defining harvest levels

Wood can be harvested by means of two modes, forest clearcutting and selective logging. Clearcutting in all forest types (I to V) consists of the complete removal of the growing stock and has land cover change implications. Barren forest land is shifted to the land pool 'other natural vegetation'. Selective logging takes place at sustainable harvest level and is permitted in natural forest types (III to V). The sustainable harvest level per grid cell is estimated as the arithmetic mean over 20 years (1986-2005) of the net change of the vegetation carbon stock CS.

$$NAI = \frac{\sum_{t=1}^{T} (CS_{t+1} - CS_t : (CS_{t+1} - CS_t) > 0)}{T}, \ \forall \ t \in T \tag{2.10}$$

NAI denotes the net annual increment if the Net Primary Production (NPP) is greater than the density-depending mortality which is inherent to the condition $(CS_{t+1} - CS_t) > 0$. The assumption is taken that the changed growth dynamics compensate the removal of the net annual increment (surplus NPP) by selective logging through reduced density-depending mortality in subsequent years and the vegetation carbon stock level is maintained.

The approximation procedure described in Step 4 has also been adopted for the estimation of sustainable harvest levels (m^3 dry matter per hectare) from aboveground vegetation carbon in mixed PFTs (tons carbon per hectare) (Table 2.2).

The regional sustainable harvest levels are illustrated in standard boxplots (Figure 2.13).

Neither sustainable harvest levels nor the growing stock are decisive in delineating the wood production potential between natural forest types (III to V) per grid cell. Further development of the model LPJ would have been required in order to distinguish between growth dynamics in potentially managed and undisturbed natural forest which is beyond the scope of the doctoral thesis. Therefore, land allocation rules (Subsection 2.3.4) and forest area per grid cell for specific forest types (Subsection 2.2.3) determine the wood production potential in natural forest types per grid cell.

Step 7: Calibration of AR area in age-class forest

In MAgPIE-F, the AR area in age-class forest is driven by the expected total demand for wood commodities in the future and the production cost advantages in different forest types to satisfy wood demand. However, there is a gap between initial modelled AR area and the actual observed AR area according to FAO (2010). The AR rate may be exogenously prescribed (Gusti et al., 2008)[10] or endogenously estimated.

[10] The amount of agricultural land that is available per year for forest establishment is estimated as output of a calibration phase. The GLOBIOM / Global Forest Model (G4M) modelling framework Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) endogenously generates afforestation and deforestation rate adjustment coefficients in the calibration against global emissions estimates provided by the IPCC (Boettcher et al., 2008, p.11). In a previous study, Kindermann et al. (2006) employ G4M, which has been calibrated against global analyses derived from remote sensing data.

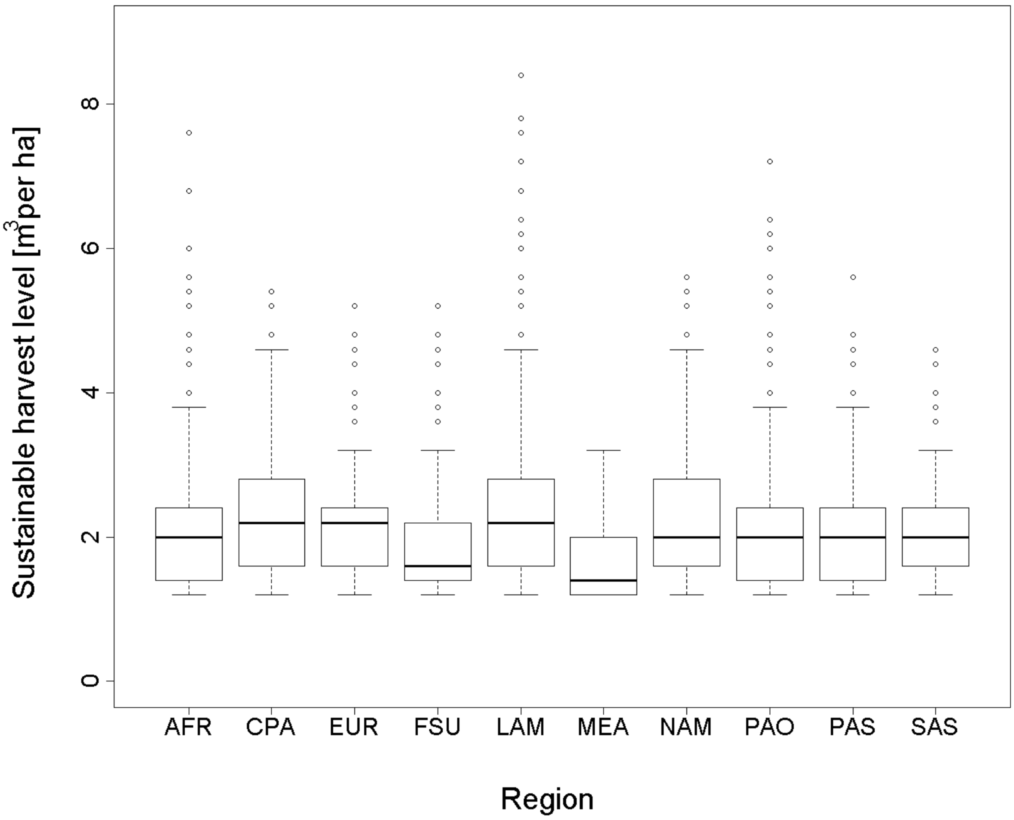

Figure 2.13: Estimated sustainable harvest level in natural forest (forest types III to V). The boxplots display the median (black line), the upper and lower quartile (box), the minimum and maximum of the distribution (whiskers), and the outlier (dots).

In MAgPIE-F, the AR area is calibrated to the actually observed AR area. The observed area of planted forest in different countries is available from FAO for the year 2000 and 2010 (FAO, 2010). The absolute decadal change in planted forest area corresponds to the net AR area.

The observed AR area amounts to 49 million hectares per decade globally and is regionally disaggregated as given in Table 2.3.

Table 2.3: Observed regional area of AR between 2000 and 2010 (Mha)

Economic region	Area [Mha]
AFR	2.1
CPA	24.4
EUR	3.1
FSU	2.0
LAM	6.3
MEA	0.5
NAM	6.0
PAO	0.7
PAS	0.9
SAS	3.3

The observed regional AR area is initiated in MAgPIE-F and becomes binding if the endogenously calculated derived demand for additional age-class forest area per region is smaller than the observed area per region. It is assumed that the adjusted area accounts for additional drivers of AR such as specific environmental policies, which are not covered in this model. The initiated AR area is assumed to be constant in the initial and second timestep (1995 and 2005) and decreases over time at a rate of 10 % until 2095. By this means, additional drivers of AR are expressed to lose importance relative to the derived demand for additional forestland for roundwood producion.

Step 8: Definition of auxiliary parameters

The need for defining two additional parameters is explained hereafter.

- Parameter on the historical and projected roundwood production share from age-class forests

In MAgPIE-F, the roundwood supply in the long run needs to be sustained, which is the reason why the forestry sector decision makers are assumed to rationally expect roundwood demand and sources of supply in the future to be based on historical evidence. Forestry decision makers expect the available natural forest area and growing stock to change in line with the historical trend and adjust their behaviour accordingly to the establishment of age-class forest. There may be a case that the expected supply of wood commodities from natural forests at different rotation lengths of age-class forest is sufficient to complement corresponding roundwood supply. In that case, the decision makers do not have sufficent incentives to increase the contribution of age-class forests to roundwood production and thus follow a prescribed historical rate. Otherwise, today's activity on age-class forest establishment is entirely aimed at covering roundwood production for tomorrow.

Miner (2010) estimates planted forests (forest plantations and planted semi- natural forests) to contribute 35 % of global roundwood production in 2000 which rises to 44 % in 2020 (Miner, 2010, p.9). Other estimates for the same year encompass industrial plantations and managed indigenous second-growth forest, (Sedjo et al. (2001) in: FAO (2002, p.18)), which make up a share of 64 % of total industrial roundwood supply (excluding woodfuel). The share is projected to rise to 85 % in 2050. Since the delineation of age-class forest in MAgPIE-F is conceptually linked to Miner (2010), the parameter values used hereafter are conservatively derived by constant percentage change of planted forests shares at roundwood production. By this means, the age-class forest contribution to roundwood production rises from 35 % in 2000 by more than 1.2 % annually, thus almost doubles until 2050, and is kept at constant value (67 %) afterwards.

- Barrier-to-implementation parameter for AR per grid cell

In a spatially-explicit land use model such as MAgPIE-F, the patterns of AR may follow the productivity of land as well as the rules of bio-physical constraints. However, the magnitude of AR per spatial unit may be unrealistically high if not restricted by further rules. Global forestry sector models (top-down models) (see Subsubsection 1.1.1) often do not take into account the barriers of implementation, which explains the relatively high estimates of the economic mitigation potential compared to bottom-up regional models (Nabuurs and Masera, 2007, p.562).

According to Gusti et al. (2008), a hurdle parameter that reflects transaction costs of land use change can be set. In GAINS (Boettcher et al., 2008), technical, infrastructural and financial capabilities of the forest establishment are grasped by the country-specific afforestation rate which corresponds to the amount of agricultural land available for forest establishment per year. Obersteiner et al. (2006) assume in the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) that 80 % of each 50 km times 50 km grid cell is available for AR per year while the rest is allocated to settlements, roads and land reserves.

Setting a barrier-to-implementation parameter is deemed essential for the restriction of land use change to forest due to unaccounted decision factors in MAgPIE-F. Barriers to the implementation stem from policy prescriptions and regulations on site selection for forest establishment. The barriers can be modelled implicitly by the share of available land per grid cell, which is available for AR activities per year.

In MAgPIE-F, a barriers to implementation parameter has been implemented in a simplified manner. The parameter value is initialized and kept constant from 1995 to 2095 at a share of 1 % that is convertible per 50 km times 50 km grid cell per time step. The values represent the average capabilities of a forest establishment set by the policy framework and conservatively excludes protected areas or areas for land development unaccounted for.

2.3.2 Cost dimension of wood production

Authors: Michael Krause, Benjamin Bodirsky, Jan Dietrich, Alexander Popp, Christoph Mueller

Conceptual approach

The economic analysis of land use dynamics between the agriculture sector, forestry sector and forest-based climate change mitigation activities in the cost- minimizing MAgPIE-F depends on the parameterization of distinct wood production cost types at a level of detail similar to MAgPIE's agriculture sector. The cost types cover:

1. the initial costs of land conversion,
2. the costs of forest regeneration and wood harvest,
3. the recurrent costs of forest management, and
4. the wood transport costs to markets.

Wood commodities are produced by means of a Leontief production function, i.e. factor inputs enter in fixed proportions with zero elasticity of substitution (constant relative factor costs). Average labour and capital inputs translate into constant average costs for these variable inputs per hectare of land (cost types 1 to 3) or per m^3 of wood respectively (cost type 4). Global labour and capital markets are not modelled explicitly which is inherrent to partial equilibrium land use optimization models such as MAgPIE-F. The assumption is taken that an unconstrained variable factor shift to the forestry sector at a given factor cost allows coping with prescribed changes in factor demand. As such, it implies a perfect price elasticity of variable factor supply, i.e. the percentage change of supplied quantity divided by the percentage change of variable factor price is infinite. At the same time there are no variable factor substitution and demand responses to variable factor prices, i.e. the variable factor demand is perfectly price inelastic. The percentage change of demanded quantity divided by the percentage change of variable factor price is zero. The production cost heterogeneity per m^3 of wood commodity in cost types 2 to 3 results from spatially-explicit productivity levels per hectare of land.

Land conversion costs

- Introduction and rationale

Land conversion costs accrue for land development at different stages of land use such as: 1) the clearing of wilderness (unused land) to establish managed forests, 2) forest clearing for agriculture and 3) the conversion of agricultural land for residential and commercial areas. The method of calculating total land conversion costs depends on the spatial scale of modelling, implying different levels of detail in accessible datasets.

On a subglobal scale, the costs of conversion of agricultural land to developed land may be grasped by defining the value of infrastructual improvements in the average value of developed land (Plantinga et al., 2002). Engineering case studies reveal details on the composition of total land conversion costs at different transition stages from unused land to developed land (Porr et al., 2009; Lazdins et al., 2009; Simorangkir, 2007). Apart from the need for investments in infrastructure, the total costs of land conversion per hectare depend on the method of land clearing (depending on topography, soil conditions, vegetation type, socio-cultural background), and the subsequent land use type and required site preparation measures (Porr et al., 2009; Lazdins et al., 2009; Simorangkir, 2007). There is a multitude of possible procedures to clear land, but bulldozers and front-end loaders or excavators and root rakes are commonly used to remove stumps in developed countries (Porr et al., 2009; Coder, 2003; Laitila et al., 2008; Turnbull et al., 1992). Whereas in a variety of developing countries traditional slash-and-burn practices (Cassel and Alegre, 1994) and clearing plantations by fire for replanting (Simorangkir, 2007) are still common in addition to mechanical land conversion.

On a global scale, consistent detailed land conversion cost estimates from unused land to developed land are not available. The GTAP approach establishes regional marginal access cost functions into inaccessible land by means of regional constant elasticities as a function of the available land share. The approach has its merit in desirable convex functional forms with strictly monotonic, overproportionally increasing slopes towards the asymptote of totally remaining inaccessible forest land (Gouel and Hertel, 2007). Historical regional forest land prices serve as a proxy to determine the magnitude of the initial conversion costs. However, the identification of elasticities appears arbitrary where observed forest land prices may be a poor proxy for access costs at the extensive margin if land markets do not exist as in major parts of tropical regions. Furthermore, the endogenous update of regional costs without reference to spatially-explicit land use dynamics is not feasible in MAgPIE. Another approach at global scale builds upon datasets of the Global Timber Model (GTM) database (Sohngen et al., 2009; Sohngen and Tennity, 2004) as outputs of the GTM by Sohngen et al. (2001); Sohngen and Mendelsohn (2003). They consist of country-level marginal access costs which comprise the cost of building roads and other infrastructure to access forests (Sohngen et al., 2009). Technically, they correspond to the NPV of future forest land and the revenue from harvesting the last hectare of old growth forest in equilibrium. The NPV of future forest land bases on the Faustmann formula (Faustmann, 1995; Hartman, 1976) which reflects the capitalized periodic land rent in forestry land use in perpetuity.

The employed concept in MAgPIE-F is based on the conceptual adaptation of outputs of the GTM for reasons of compatibility to the existing MAgPIE functionality. The detailed country-wise depiction of land conversion costs is beyond the scope of this study. Constant global land conversion costs have been estimated as a parameter for the first time in MAgPIE and its extension MAgPIE-F.

- Implementation into MAgPIE-F, assumptions and employed datasets

The marginal access costs for a hectare of accessed old-growth forest for subsequent forestry use (Sohngen et al., 2009) serve as a starting point for estimating the costs of converting land from natural forest (forest types III to V, Figure 2.4) to age-class forest or agriculture[11]. Marginal access costs are 'equivalent to the marginal value of the stumpage on that site', which denotes the summed value of harvesting current old growth forests and the NPV of growing forest on the site in the future (Sohngen et al., 2009, p.19). In MAgPIE-F land use dynamics are endogenously determined, i.e. the land allocation to forestry in the future is not prescribed. Accordingly, the NPV of land in future forestry production, which is the LEV, has been subtracted from the marginal access costs with subsequent forestry land use MAC^{fore} per country k and timber management type mt (Sohngen et al., 2009) leaving the marginal costs of clearing contemporary natural forest for subsequent land uses. Since equilibrium rents of land in any subsequent land use are MAgPIE-F outputs, the result corresponds to the minimum marginal

[11]Intact and frontier forest in MAgPIE-F roughly correspond to old-growth forest per definition. The terms 'access costs' and 'conversion costs' have the same meaning but help distinguishing input datasets from estimates used in MAgPIE-F.

conversion costs MCC^{any}_{reg} excluding the costs of additional land but covering the costs of infrastructure, land clearing and site preparation. The timber management type area $A_{mt,k}$ -weighted mean of minimum marginal access costs from old-growth forest to any subsequent land use type have been calculated for each country k and aggregated to regional groups reg by MAgPIE-F's natural forest area A^{NF}_{k} -weighted mean. Two regional groups are distinguished between developing and transitional countries[12], and developed countries[13].

$$MCC^{any}_{reg_k} = \Big[\sum_{k=1}^{K} \frac{\sum_{mt=1}^{MT} \Big((MAC^{fore}_{mt,k} - LEV_{mt,k})A_{mt,k}\Big)}{\sum_{mt=1}^{MT} A_{mt,k}} A^{NF}_{k}\Big] / \sum_{k=1}^{K} A^{NF}_{k}, \quad \forall\ k \in K,\ \forall\ mt \in MT \tag{2.11}$$

Finally, unit conversion costs are kept constant at the magnitude of 1000 US$ per hectare for the developing region group, where 7500 US$ per hectare is accrued in the developed region group. These conversion cost values are assumed to apply to the conversion of other natural vegetation as well.

- Validation of land conversion cost estimates

Engineering case studies are used to confirm the magnitude of estimated average land conversion costs. In developed countries, case studies on mechanized land clearing draw a range from 1510 US$ per hectare in Latvia (Lazdins et al., 2009)[14], 2240 US$ per hectare in Australia (Turnbull et al., 1992)[15], 3710 US$ per hectare on average in USA (Porr et al., 2009)[16] to 13950 US$ per hectare (Martin and Meader, 2000) in Massachusetts, USA. These land clearing methods either only cover stump removal, or add transport off-site (Lazdins et al., 2009) and grading (Martin and Meader, 2000). However, these values exclude the costs of road construction and other site preparation measures such as drainage ditchs or mechanical weed control. Topsoil retaining measures may also add on top of estimates (Porr et al., 2009). Tree removal in urban forests in California, USA sums to 10500 US$ per hectare (McPherson et al., 1999)[17], in Colorado up to 18600 US$ per hectare (McPherson et al., 2004)[18] which does not trigger additional costs as infrastructure is already in place.

In developing tropical countries, slash and burn is commonly practiced by smallholder farmers who burn unused natural vegetation to obtain fertile agricultural land. This is done for a certain time period before land is abandoned for natural revegetation. In contrast to mechanical land conversion practices, the cost-intensive machinery input is foregone (Varma, 2003). The conversion of forest to rangeland in Bolivia costs up to 660 US$ per hectare, including clearing tax, as labour wages are less expensive than in developed countries and machinery use is limited

[12] Countries in Sub-Saharan Africa, Centrally-Planned Asia, Former Soviet Union, Latin America, Middle East and North Africa, Pacific Asia and South Asia are attributed to the developing region group.

[13] Countries in Europe, North America and Pacific OECD regions are subsumed under the developed region group.

[14] The costs account for stump removal, transport of stumps and site preparation. The employed currency exchange rate is 1 LVL = 1.88 US$.

[15] The costs account for stump removal by excavator and cable logging.

[16] The costs comprise conventional land clearing whereas topsoil-retaining measures add on top.

[17] The cost value is based an average on density of 34 trees per hectare and 343000 US$ for 1300 trees removed.

[18] The cost value is an average based on density of 55 trees per hectare and 130487 US$ for 400 trees removed. All costs are calculated as constant US$ in 2005.

(Merry et al., 2002). In Indonesia, mechanized land clearing without burning sums the 550 US$ per hectare in logged forest on peat soils (Simorangkir, 2007)[19]. The difference in mechanized land clearing costs compared to developed countries may be explained by the inclusion versus exclusion of capital costs for excavators and bulldozers in cost calculations. In Brazil's Southern Mato Grosso, the shift of animal power-based to mechanized land preparation has been associated with increasing costs for agricultural land preparation (Sanders and Bein, 1976). It can be assumed that the costs of natural forest land conversion increase with advances in technology employed. There is evidence that the costs of slash and burn to global society exceeds the private benefits to operators, i.e. the contribution to global warming versus the cost savings compared to mechanized land clearing (Varma, 2003).

However, negative external effects to a global society are not included in conversion cost calculation. However, the direct costs of mechanical land conversion in developing and transitional countries support an approximate value of 1000 US$ per hectare for Sub-Saharan Africa, Centrally-Planned Asia, Former Soviet Union, Latin America, Middle East and North Africa, Pacific Asia and South Asia. Studies from developed countries and Sohngen et al. (2009) justify 7500 US$ per hectare to accrue in Europe, North America and Pacific Organisation for Economic Co-operation and Development (OECD) regions.

Cost of forest regeneration and wood harvest

- Introduction and rationale

MAgPIE uses the GTAP database version 7 as a major reference to calculate average costs of factor inputs such as chemicals, labour, and capital per hectare for several agricultural crop types in 10 economic regions. Because the GTAP database version 7 comprises the forestry sector and the value of factor inputs from several other sectors in a consistent way, it is favoured in CGE model applications (Sohngen et al., 2009). Nevertheless, its use for the forestry sector in MAgPIE has been rejected for two reasons. First, the reference to a forestry area is missing and thus highly speculative factor costs per hectare would have been generated, depending on the definition of forestry area. Second, apart from missing disaggregation of forest types or management activities as a second reason. Instead, the cost of forest regeneration and wood harvesting have been derived from the GTM database version 5 (Sohngen et al., 2009). Additional references are included to complement and validate total roundwood production costs (Elias, 1998; Fath, 2002; Holmes et al., 2002; Sathaye et al., 2005).

- Implementation into MAgPIE-F, assumptions and employed datasets

Average regeneration costs per country and timber management type are directly taken from the GTM database in year 2000 US$ per hectare values (Sohngen et al., 2009).

Average harvest costs are broadly defined as the costs of forest road construction and maintainance, and logging and hauling to mills (Sohngen et al., 2009). These costs are provided on a per m^3 basis as the difference between quality adjusted timber log prices P^{log} and quality adjusted stumpage prices P^{stump} per country k and management type mt. The resulting marginal costs of harvesting are assumed to correspond to average total costs and marginal revenues in perfectly competitive wood commodity markets for simplicity reasons. The present study makes

[19] All costs are calculated as constant US$ in 2005.

use of per hectare harvest costs C^{harv} which ought to reflect proportionally diminishing harvest costs per m^3 on forested land with increasing land productivity and forest age. The latter may be associated with a change in machine relocation overhead costs (Russell et al., 2005). Thus, some calculations became necessary.

$$C^{harv}_{mt,k} = \frac{Y_{mt,k}}{A^{harv}_{mt,k}}(P^{log}_{mt,k} - P^{stump}_{mt,k}),\ \forall\ k \in K,\ \forall\ mt \in MT \tag{2.12}$$

The above equation calculates the harvest loss adjusted average harvested roundwood volume per hectare from the total derived yield as the quotient of roundwood production Y and area harvested A^{harv} per year multiplied by the average harvest cost per m^3. It is assumed that each hectare harvested is entirely cleared and thus derived yields correspond to growing stock at a given average rotation length.

Regeneration and harvest costs are upscaled to economic regions and forest types I and II (softwood and hardwood age-class forest) and forest types III to V (natural forest) by regeneration and harvested area-weighted mean. While harvested area of different timber management types mt per country k is directly available from the GTM database, the regeneration area A^{regen} is derived by making use of harvested area A^{harv} and net area change ΔA^{net} from observed data for 2005 (FAO, 2006).

$$A^{regen}_{mt,k} = A^{harv}_{mt,k} + \Delta A^{net}_{mt,k} : A^{harv}_{mt,k} \leq -\Delta A^{net}_{mt,k},\ \forall\ k \in K,\ \forall\ mt \in MT \tag{2.13}$$

Thus, the regeneration and harvest costs per hectare, per region i and forest type ft are

$$C^{regen}_{ft,i} = \frac{\sum^{MT,K}_{mt_{ft}=1,k_i=1}\left(C^{regen}_{mt,k} A^{regen}_{mt,k}\right)}{\sum^{MT,K}_{mt_{ft}=1,k_i=1} A^{regen}_{mt,k}},\ \forall\ k \in K,\ \forall\ mt \in MT \tag{2.14}$$

$$C^{harv}_{ft,i} = \frac{\sum^{MT,K}_{mt_{ft}=1,k_i=1}\left(C^{harv}_{mt,k} A^{harv}_{mt,k}\right)}{\sum^{MT,K}_{mt_{ft}=1,k_i=1} A^{harv}_{mt,k}},\ \forall\ k \in K,\ \forall\ mt \in MT \tag{2.15}$$

In two regions there have been missing values in either Hardwood (Centrally-Planned Asia) or Softwood (Pacific Asia) planted and harvested area of age class forest. Missing values have been substituted by global mean cost values accordingly and are explained by preferred Softwood and Hardwood for wood production in Centrally-Planned Asia and Pacific Asia respectively.

- Validation of regeneration and harvest cost estimates

Sathaye et al. (2005) did an extensive review on economic parameters for short and long rotation plantations in major economic regions in the world which have been used to put estimated costs of forest regeneration and harvest per hectare into perspective (Table 2.4). By doing so, observed harvest costs per m^3 of biomass have been multiplied by the MAI of tons biomass per hectare and year, and the inverse of an assumed average wood density of 0.5 to obtain harvest costs per m^3 of biomass per year. The range of total per hectare harvest cost values is obtained by multiplication with the rotation length for short and long rotation systems (Sathaye et al., 2005). The harvest costs have been discounted to the NPV by a discount rate of 5 % for developed regions (Europe, North America, Pacific OECD) and 10 % for developing and transition regions[20] (Table 2.4).

The magnitude of results is in line with Sathaye et al. (2005) and substantiated by Brown (1999) that the most significant costs are harvesting costs among others not modelled explicitly in MAgPIE-F such as land, labour and finance costs (e.g. interest paid on project loans). Estimated regeneration costs are generally lower, particularly in Europe and North America, since the land and establishment costs are included in datasets compiled by Sathaye et al. (2005).

Regarding natural forests, other studies estimate forest harvest costs per hectare in Mozambique at 36 US$ per m^3 (Fath, 2002, Tab.4), the Amazon at 14 US$ per m^3 (Holmes et al., 2002), and in Indonesia at 12 US$ per m^3 (Elias, 1998). For the ease of comparison, these values can be multiplied by the estimated average growing stock per region in MAgPIE-F[21] (Subsection 2.3.1) resulting in harvest costs at 3450 US$ per hectare in Sub-Saharan Africa, 1500 US$ per hectare in Latin America and 1800 US$ per hectare in Pacific Asia. Thus, the magnitude matches well with the estimated harvest cost in natural forest ('Other' in Table 2.4).

Recurrent cost of forest management

- Introduction and rationale

The cost of managing the forest throughout the forest rotation length constitutes an important component of total factor costs. They comprise the cost of ameliorative liming, thinning, pruning of softwood timber trees with the respect to the maintenance of infrastructure such as roads or drainage systems at different forest development stages. Since the GTM database (Sohngen et al., 2009) does only provide regeneration costs and derived harvest and hauling costs, MAgPIE-F's regional recurrent costs per hectare had to be derived from additional references.

- Implementation into MAgPIE-F, assumptions and employed datasets

In MAgPIE-F, the recurrent costs accrue for aggregated regionally representative management bundles. These management bundles include the combination of a range of measures such as weeding, pruning, thinning, forest protection and monitoring and road maintainance. Regional constant costs per hectare are estimated for age-class forest. The recurrent costs of a long-term plantation forest calculated for seven countries according the Comprehensive Mitigation Assessment Process (COMAP) (Sathaye et al., 2001, 2005) serve as a proxy for age-class forest in MAgPIE-F. Age-class forest (forest types I and II) subsumes plantations and semi-natural forests and recurrent costs may thus be influenced by a broader range of environmental conditions and applied management regimes than referred to in Sathaye et al. (2001, 2005). This adds uncertainty on the magnitude of actual recurrent costs. The assumptions are: (1) the recurrent

[20] The regional mapping of MAgPIE-F to Sathaye et al. (2005) is Europe to EU, Centrally-Planned Asia to China, South America to Central America, Sub-Saharan Africa to Africa, South Asia to India, Former Soviet Union to Russia, North America to USA, Pacific Asia to Oceania.

[21] The growing stocks amount to 96 m^3 per hectare in Sub-Saharan Africa, 109 m^3 per hectare in Latin America and 152 m^3 per hectare in Pacific Asia.

Table 2.4: Estimated factor costs in forestry operations in different forest types (US$const2000/ha)

Economic region	Estimated cost						Observed cost	
	Softwood		Hardwood		Other			
	RC	HC	RC	HC	RC	HC	RC	HC
AFR	395	7381	348	2858	0	2649	871 to 1104	2570 to 8328
CPA	74	1587	135	3048	0	1587	245	399 to 4266
EUR	53	7695	18	5191	0	7002	1068	441 to 4880
FSU	17	2647	18	1720	0	2305	123	170 to 1152
LAM	676	2657	662	2282	0	1166	394 to 716	2331 to 3750
MEA	395	924	348	358	0	629	-	-
NAM	169	5055	33	3983	0	4438	2277	517 to 2650
PAO	347	3629	1805	5897	0	3913	-	-
PAS	175	5122	50	820	0	1426	467 to 1897	805 to 947
SAS	88	3135	70	601	0	802	340 to 778	1015 to 6446

RC=Regeneration cost, HC=Harvest cost

cost relation between regions is constant, i.e. the underlying labour and capital costs relations do not change and (2) adopting recurrent cost levels per hectare from Sathaye et al. (2001, 2005) improves total production cost estimates in the absence of more accurate datasets.

Regional recurrent costs of forest management and monitoring are depicted in Table 2.5.

Table 2.5: Estimated recurrent costs in forestry operations (US$const2000/ha)

Economic region	Value
AFR	116
CPA	6
EUR	93
FSU	2
LAM	50
MEA	45
NAM	42
PAO	45
PAS	41
SAS	21

- Validation of recurrent cost estimates

The low cost of forest inventory and management plans in Latin America are exemplified by Merry et al. (2002) in Bolivia not to exceed 6.5 US$ per hectare. This is a magnitude of 10 lower than estimates in MAgPIE-F for Latin America due to the difference of forest types, i.e. natural forest versus plantations, and the annual allowable cut. Relatively high recurrent costs in Sub-Saharan Africa may be explained by intensive management of forest plantations. In Central Europe, 120 US$ per hectare[22] and year are spent for administering forests including costs of management planning and operations (Bis, 2009).

Intra-regional spatially-explicit transport costs

Authors: Michael Krause, Benjamin Bodirsky, Jan Dietrich, Alexander Popp, Christoph Mueller

- Introduction and rationale

Spatial land-use patterns reflect the complex interplay of land suitability, demand for land-intensive products, availability of inputs, and historic patterns. The cost of variable inputs, such as chemicals, as well as the marketability of products, strongly depend on transportation costs.

The cropland expansion rate in MAgPIE so far is constrained by maximum expansion rates, reflecting the idea that it takes some time to build the infrastructure that is necessary for the expansion of agricultural land. While this captures some mechanisms of land expansion, it falls short of reproducing observed expansion patterns, especially in remote areas such as Latin America. The transport cost-based managed land conversion in MAgPIE primarily aims at

[22] The employed currency exchange rate is 1 Euro = 1.4 US$.

substituting the physical constraint of maximum cropland expansion rates by endogenous land use optimization decisions and taking the distance to markets into account. By this means, MAgPIE responds to the criticism that pertains to heavily constrained models to possibly produce biased outputs according to researcher's needs. The undirected spatially-explicit cropland land expansion in previous model versions (Lotze-Campen et al., 2008; Popp et al., 2010) is extended to directed spatially-explicit managed land conversion (cropland, pasture land and planted forest land) based on transport cost gradients. By this means, the model strives for improving intra-regional spatially-explicit land-use patterns by providing a flexible approach to model the extensive margin of multiple managed land-use classes consistent with the economic theory behind v. Thuenen's model.

- Employed datasets

The global sum of crop-specific transport costs is derived from the GTAP database version 7 (Narayanan and Walmsley, 2008). GTAP transport sectors cover Trade Services, Water Travel, Rail Travel, Road Travel, and Air Travel. The costs of transport comprise the transport of agricultural inputs and transport of the output from the agriculture sector to secondary sectors of processing. The transport costs of secondary sectors are proportionally allocated to the input value of non-service and non-infrastructure input sectors to agriculture. The transport costs between agricultural and forestry sectors add to the respective transport costs. The global sum of crop-specific transport costs is discounted to the year 1995 to be time-consistent with the other model input.

Other than datasets on unit transport costs derived from the GTAP database, a dataset on the physical distance to major cities has been obtained from the European Commission Joint Research Centre (Nelson, 2008). Intra-regional spatially-explicit total transport costs of agricultural and forestry wood commodities had to be computed in MAgPIE. The 30 arc-second resolution map on travel time to the nearest large city provides the physical component in total transport cost calculation (Nelson, 2008). The dataset is based on multiple biophysical, administrative and transport mode depending indicators which make up the friction surface that determines the speed needed to cross grid cells (Nelson, 2008). The cumulated time value needed to reach an urban center of 50000 inhabitants at minimum stands as a static proxy for the accessibility of a grid cell (Nelson, 2008). The dataset has been explicitly used in compiling an agglomeration index to uncover global urban-rural gradients (Uchida and Nelson, 2009), but is also considered useful for transport cost modelling. The major assumption pertains to the use of the indicator of time instead of physical distance. Since we keep unit transport cost calculations simple we argue that the indicator of transportation time needed for each commodity on average is greater than the indicator of physical distance due to the fact that the dimension of existing infrastructure, topography and country borders is explicitly taken into account. We further assume existing transportation modes, infrastructure and urban areas to remain constant by type and magnitude in the future. The dataset has been aggregated by the arithmetic mean of land bearing grid cells in coarser resolution to correspond to MAgPIE's resolution of 0.5 arc degrees. Missing values have been removed by nearest neighbor value assignment[23].

- Implementation into MAgPIE-F and assumptions

[23]The data manipulation has been conducted in ARCGIS 9.2.

For the implementation in MAgPIE-F two datasets have been used: 1. the spatially-explicit travel-time data and 2. the average transport costs per ton per minute. Whereas the travel-time dataset could be used directly the second dataset has to be derived first. This is done by calculating the worldwide, crop-specific transport power by multiplying the travel-time with crop-specific and spatially-explicit data on production quantities (calculated by multiplying LPJ yields with LPJ sowing area (Fader et al., 2010)) and calculating the global sum. Dividing the global sum of crop-specific transport costs by this global transport power delivers the average, crop-specific transport costs per ton per minute. Unfortunately, GTAP uses different crop categories as LPJ which leads to many problems when mapping crops to each other. Therefore, only rice and wheat delivered well-defined mappings in the agriculture sector. To prevent model biases due to bad crop mappings, any MAgPIE-crop uses the transport cost value of wheat. The current version of MAgPIE employs the cellular distance dataset and a crop-specific transport cost by multiplying them internally to the cellular transport-cost dataset, which is then used. Therefore, the structure is already fully prepared to deal with crop-specific transport costs. Hence, better data on average transport costs can be easily implemented when available. As a preliminary solution, wood commodities are intra-regionally transported at the cost per ton per minute of agricultural commodities.

Mathematically, the total transport costs per minute of travel time $p^{ctr}_{t,f}$ for each time step t and commodity in production activity $prod_f$, over all spatially-explicit units j are obtained by

$$p^{ctr}_{t,f} = \frac{\sum_{j=1}^{J}(prod_{t,j,f}time_j)}{\sum_{j=1}^{J}(prod_{'y2000',j,f}time_j)},\ \forall\ t \in T,\ \forall\ f \in F \tag{2.16}$$

It is assumed that the transport costs change proportionally to changes in transportation time while transportation infrastructure remains in the same state it was in 1995. Furthermore, all transport costs incur for the transport to the closest larger city (with 50000 inhabitants or more), i.e. neither to smaller cities nearby, nor to larger cities somewhere else in the region or to other regions.

The resulting transport costs amount to 0.426 US$ per ton of dry matter per minute of transportation time.

$$C^{trans}_{t,f,wc} = \sum_j \left(f^{fprod}_{t,j,wc}(x_t) p^{dist}_j p^{ctr}_{t,f} \right),\ \forall\ t \in T,\ \forall\ f \in F,\ \forall\ wc \in WC \tag{2.17}$$

The transport cost per minute travel of time sums to the total transport cost per wood commodity in production activity by multiplication with the grid cell-specific distance p^{dist} and production quantities f^{fprod}.

2.3.3 Demand for wood commodities

Authors: Michael Krause, Susanne Rolinski, Hermann Lotze-Campen

Introduction to commodity demand modelling

In MAgPIE, the demand for food and feed has been calculated by making use of a non-linear regression analysis of GDP per capita and calorie intake per capita from cross-sectional datasets (Lotze-Campen et al., 2008). Animal products are expressed as a share of total calorie intake per capita (Lotze-Campen et al., 2008). In order to determine the region-specific demand for agricultural commodities at the farm gate derived from calorie intake, food balance sheets (United Nations, 2012) were used to map the calorie intake per capita to the calorie supply by different food items in specific regions. The food balance sheets were adapted to express the per capita supplies in terms of dietary energy value, protein and fat composition from MAgPIE's crop types (United Nations, 2012). The derived demand for food and feed- specific crop types is subject to optimization in each decadal time step and updated in a recursive-dynamic mode. Agricultural commodity demand for food and feed energy is fulfilled by 18 cropping activities[24]. Improved global food demand projections for the 21st century by means of mixed effect regression modelling are being developed for agriculture in MAgPIE co-evolutionary to the implementation of the forestry sector and forest commodity demand projections.

Extensive quantitative research has been done on the econometrically derived demand for wood commodities at country (Hair, 1967) and multi-country (Buongiorno, 1977) scales by means of time series or cross-sectional data and correlation of income and consumption analogous to Engel curves of consumer theory. More sophisticated econometric models (Buongiorno, 2003) with the focus on fixed and random effect regression analysis, where consumption is a function of price and income (Buongiorno, 1978; Baudin and Lundberg, 1987; Uutela, 1987; Chas-Amil and Buongiorno, 2000) are all based on panels with time-series and cross-sectional data for a range of countries. Another study uses domestic and import prices in addition to additional demand shifting factors to explain forest commodity demand (Brooks et al., 1995). A comparison on the demand equations for forest products was done by Simangunsong and Buongiorno (2001). Recent global land use modelling approaches either link demand for final forest products to econometrically estimated price elasticities of demand and demand updated for each projected year by demand shifters such as GDP (Sohngen et al., 2001; Kallio et al., 2004) or they non-linearly regress food and wood demand to GDP and population changes (Havlik et al., 2011).

Conceptual approach on estimating regional demand for wood products

In MAgPIE-F, the forestry sector faces per-capita demand for roundwood in four categories reflecting the apparent regional consumption per capita[25] of four wood industry & forestry products, hereafter denoted as wood products[26]. The wood products are mapped to FAO categories (FAO, 2006). The roundwood equivalent of the per-capita demand of wood products is linked to domestic derived wood removals by input-output coefficients and self-sufficiency rates (FAO and UNECE (2005, p.43), FAO (2006))[27].

The change in the total demand for wood products is driven by population change, regionally-aggregated GDP per capita over time and time itself. In addition, expectations on the total

[24]The cropping activities cover temperate cereals, maize, tropical cereals, rice, five oil crops (rapeseed, soybeans, groundnuts, sunflower, oilpalm), pulses, potatoes, cassava, sugar cane, sugar beets, vegetables/fruits/nuts, cotton, fodder, pasture.

[25]That is the domestic production minus export plus import quantities divided by the regional population, see Subsubsection 2.3.3.

[26]This term is used for simplicity.

[27]Subsubsection 2.4.2

future wood product demand do matter. Changes in the expected regional wood product demand per capita in the future are simulated by changes in regionally-aggregated GDP per capita for the year in future when forests are deemed mature for harvest. Thus, regional per-capita demand is satisfied after a predefined minimum rotation length following FAO (Del Lungo et al., 2006) and the influence of other factors expressed by shifts in the surrogate factor time (Subsubsection 2.4.2).

The wood commodities are displayed in bold, wood products are shown in italic and derived intermediate products are presented in default fonts (Figure 2.14).

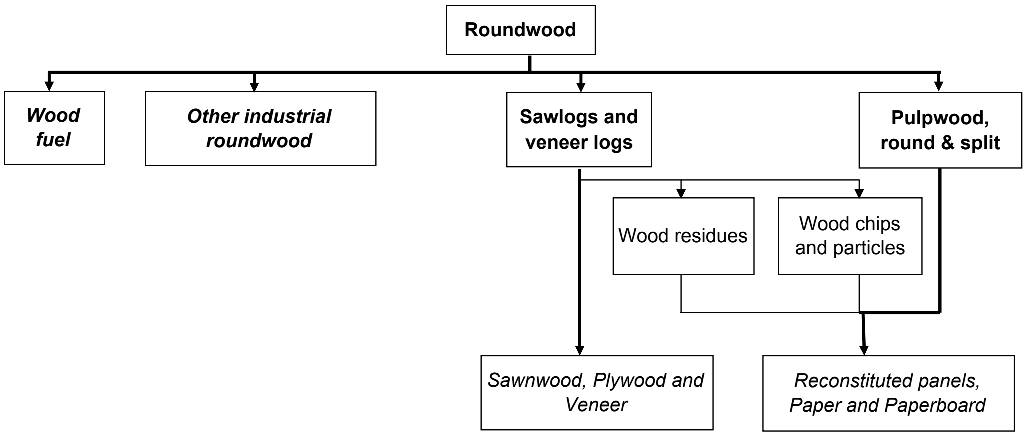

Figure 2.14: Flow chart of roundwood consumption in wood products

The regional consumption of the four wood products

- Sawnwood, Veneer sheets, Plywood (SVP)
- Wood Pulp (Intermediate, proxy for Reconstituted panels, Paper and Paperboard (RPPB)) (WPP)
- Other industrial roundwood (End product) (OIRWD)
- Woodfuel (End product)[28] (WF)

is multiplied by regional self-sufficiency shares derived from historical statistics (FAO, 2006) to estimate the domestic production share of domestically consumed wood products. These self-sufficiency shares are directly derived as the ratio of average SVP, WPP and WF production data from statistics and the corresponding estimated average apparent consumption. OIRWD is assumed to be entirely consumed domestically due to the missing production data. The consumption of Reconstituted panels[29], Paper and Paperboard (RPPB) (FAO, 2006) is strongly simplified and only implicitly included by analysing the consumption of domestically produced WPP. Therefore, the consumption of recycled paper is assumed to remain constant. This simplification requires subsequent analysis in future studies but allows circumventing inconsistencies such as double counting in summing up intermediate inputs into RPPB in the first version of

[28] Fuelwood and charcoal
[29] Particle board and fibreboard

wood product demand analysis. Burnt wood residues from industrial processing are not covered by WF consumption.

The domestic production of wood products translates into the regional derived demand for four wood commodities,

- Saw logs and Veneer logs (SLVL)
- Pulp logs (PL)
- Other industrial roundwood (Raw material) (OIRWD)
- and Woodfuel (Raw material) (WF)

via statistically-derived self-sufficiency shares for wood commodities and via conversion efficiency factors to calculate roundwood equivalent units. The assumption holds that wood residues such as wood chips and particles from wood processing in saw mills are included in the production of plywood in 'SVP' and 'RPPB' as a constant share of the input quantity consumed, where also net imports are included (1 minus self-sufficiency share of consumed pulp logs and saw logs). The derived demand for wood commodities is finally equated to the regional production quantity in roundwood equivalents.

The derived demand for wood commodities in MAgPIE-F has to be consistent with the MAgPIE framework. It is expanded by taking time as a factor in the regression analysis explicitly into account. The goal is to project the derived demand for wood commodities by mixed effect regression models (Pinheiro and Bates, 2000) which indicate whether a covariate that is categorial such as time has an uncontrolled, i.e. random effect on the result of commodity demand or not. LME regression models for each wood product link the apparent consumption to the independent variable 'GDP per capita' and the factor (grouping covariate) 'year' to project demand changes into the future and account for temporal effects. In a LME model 'a fixed-effects term ... describes the behaviour of the entire population ... a random-effects term describes the distribution within the population of a coefficient' (Pinheiro et al., 2007, p.52). Such random effect adds on top of the fixed effect of the independent variable, i.e. GDP per capita, and is useful to grasp other non-explicated variables that may also impact commodity demand. In case of wood commodities, other non-explicated variables may be the substitutional or complementary effect in demand due to own-price and cross-price elasticity of substitutes and complementary goods. The analysis is based on pooled time-series cross-sectional data of wood consumption per capita per year and GDP per capita per country per year.

In contrast to the Analysis of covariance (ANCOVA) uneven sample sizes between the factors are allowed in mixed effect models which is commonly required for FAO time-series multi-country data. Like other regression models, heteroscedasticity, the non-homogeneous distribution of variances is a threat to the reliability of predicted values because variances vary with the effects being modelled and errors are correlated and non-normally distributed. The remedy to heteroscedasticity in mixed effect models is the introduction of variance functions (Pinheiro et al., 2007, p.206ff), which is beyond the scope of the doctoral thesis.

In case LME regression fits failed, non-linear regression models or plausible assumptions on apparent consumption in the future have been applied.

Employed datasets

Time-series cross-sectional data on country-level production, exports and imports of wood products form the backbone of calculating the consumption of SVP (1994 to 2008), OIRWD (1980 to 2008), WPP (1980 to 2008), and WF (1980 to 2008) (FAO, 2006). In conjunction with country-level datasets on GDP per capita at constant 2005 US$ level (The World Bank, 2012) and population (FAO, 2012) missing values in any of the datasets per year and country led to the exclusion from regression analysis. Conversion factors are taken from FAO and UNECE (2005) assuming similar wood conversion technologies (e.g. frame saws in sawmills) like in Europe and North America.

The dependent variable is defined as the apparent wood product consumption per capita Z in historical years T, wood products WP and countries K.

$$Z_{t,wp,k} = Pro_{t,wp,k} + Imp_{t,wp,k} - Exp_{t,wp,k}, \ \forall\ wp \in WP, \ \forall\ t \in T, \ \forall\ k \in K \tag{2.18}$$

with Pro denoted as production, Imp import and Exp export, neglecting changes in stocks (FAO and UNECE, 2005).
Table 2.6 glances at descriptive statistics of both, the dependent and predictor variables.

Models of demand for wood products

The three-step procedure in demand modelling,

1. tests pooled data regression models. Models with a minimum fraction of the variance explained by the model qualify for the testing of random effects added by the factor time in the regression coefficient.

2. prescribes historical values if pooled data models do not show sufficient prediction power of GDP per capita to explain wood product demand, and

3. tests and applies a linear mixed effect models for the wood products that qualify from Step 1.

Step 1
Pooled simple regression models were tested for their power of explaining wood product demand per capita by GDP per capita[30].

Results were improved in terms of the minimized sum of squares of the residuals and improved homoscedasticity of variances by square root transformation of the dependent and predictor variables for Sawnwood, Veneer sheets, Plywood (SVP) and Wood Pulp (WPP). Still, WPP did not show a satisfactory reduction of hereroscedasticity. The division of pooled data into intervals and the calculation of interval mean values reduced the noise in indicating a sufficiently strong non-linear relationship of variables for Woodfuel (WF) and a weak linear relationship for Other industrial roundwood (OIRWD).

[30]Various models have been fitted by minimizing the sum of the squares of the residuals, tested for linear, root, power, exponential and logarithmic functions. Linear regressions were performed with function 'lm' of package 'stats' and linear mixed effect models used the function 'lmer' of the R package 'lme4' (Bates, 2010). The nonlinear functions were fitted by means of the functions 'optim' and 'nls' of the R package 'stats'.

Table 2.6: Descriptive statistics of Wood Product consumption per capita and GPD per capita

Wood Product	**N**	**Descriptive statistics**					
		Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
		Consumption per capita [m3]					
Sawnwood, Veneer sheets, Plywood	1681	0.000021	0.028	0.097	0.165	0.234	1.198
Woodfuel (End product)	1339	0.000101	0.043	0.139	0.243	0.341	1.514
Wood Pulp	1434	0.000001	0.004	0.022	0.073	0.063	1.044
Other industrial roundwood (End product)	3198	0.000004	0.007	0.028	0.039	0.058	1.018
		GDP per capita [$US\$_{const2005PPP}$]					
Sawnwood, Veneer sheets, Plywood	1681	151	4025	9650	13780	22270	74030
Woodfuel (End product)	1339	185	4318	11040	15280	24900	74030
Wood Pulp	1434	185	6526	11800	15510	24450	74030
Other industrial roundwood (End product)	3198	151	1309	4230	8723	10980	79030

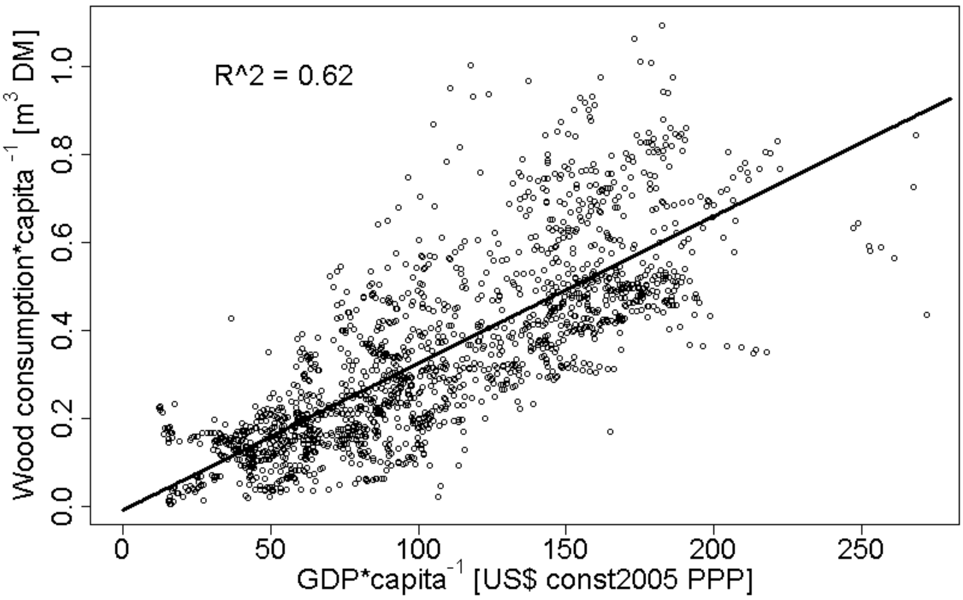

Figure 2.15: Pooled data regression of SVP consumption per capita to GDP per capita

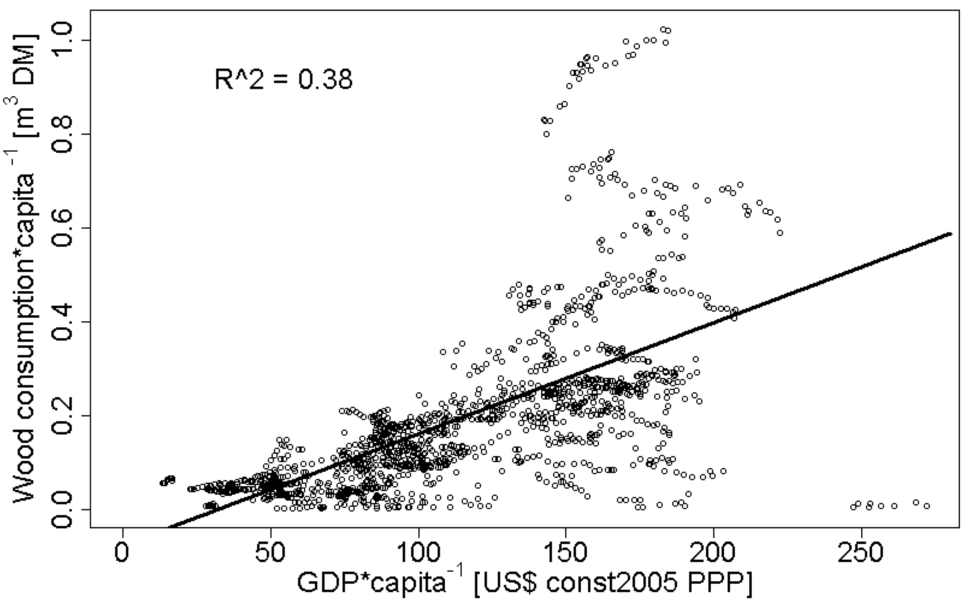

Figure 2.16: Pooled data regression of WPP consumption per capita to GDP per capita

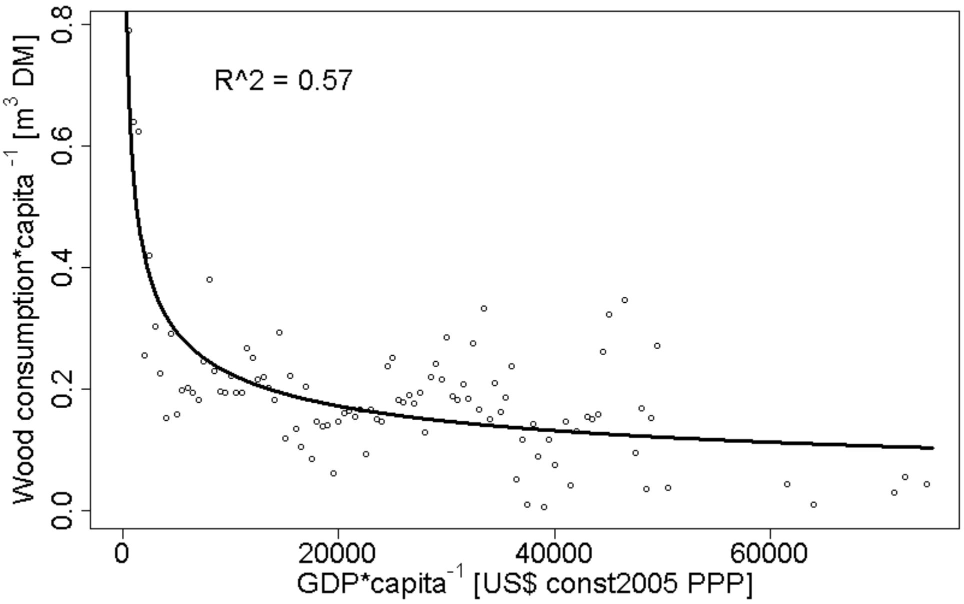

Figure 2.17: Pooled data regression of WF consumption per capita to GDP per capita

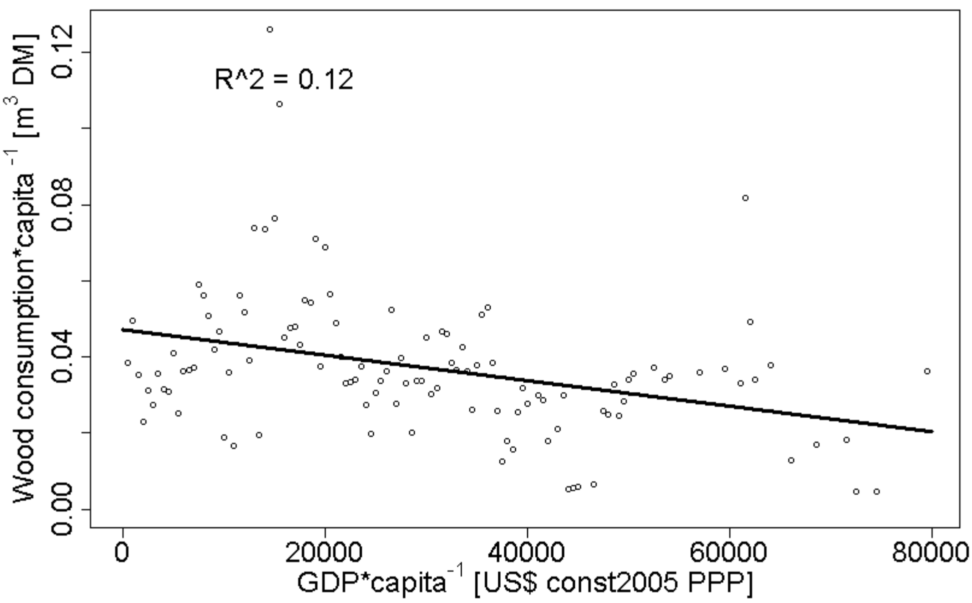

Figure 2.18: Pooled data regression of OIRWD production per capita to GDP per capita

The transformed pooled SVP consumption is best described by transformed GDP following an increasing linear relationship:

$$\widehat{Z}^{1/2}_{t,'SVP'} = 0.01 + 0.003 * gdp^{1/2}_{t,'SVP'},\ \forall\ t \in T \tag{2.19}$$

while the relationship of pooled WF consumption to GDP is explained by a decreasing root function based on interval data:

$$\widehat{Z}_{t,'WF'} = 8.0165 + gdp^{1/-2.575}_{t,'WF'},\ \forall\ t \in T \tag{2.20}$$

Step 2

WPP consumption data is only weakly explained by GDP data, which is reason to model future consumption by the population-weighted regional mean consumption. The treatment of OIWRD follows the rationale of WPP but only production data is available for OIRWD which is assumed to correspond to consumption data since trade can be neglected. Z and *pop* reflect the observed consumption per capita and population in a region $i \in I$ respectively.

$$\widehat{Z}_{t,wp} = \frac{\sum_{i=1}^{I} Z_{wp,i} pop_{wp,i} gdp_{t,wp,i}}{\sum_{i=1}^{I} pop_{wp,i}}, for\ wp \in WP\left\{'OIRWD','WPP'\right\},\ \forall\ t \in T \tag{2.21}$$

Step 3

The simple regression models do not reveal the influence of time since the models use pooled data across GDP per capita and time. However, the variation in wood product demand is hypothized to be characterized by the between-time GDP per capita variability (across years) and the within-time GDP per capita variability (for a single year). The influence of the grouping covariate 'year' on wood product demand is of central interest. The models for SVP and WF show a goodness of fit, how well the models fit the respective set of observations, with $R^2 > 0.5$. Thus they have been selected for further disaggregation.

A common further procedure entails the definition of a range of models, e.g. by letting slope and intercept to vary together, slope and intercept each to vary separately, or slope and intercept each to vary separately and sequentially for each year. The evaluation and selection of the best-fitting model, is commonly done by the Log-Likelihood ratio test, the Bayesian Information Criterion (BIC) or the Akaike Information Criterion (AIC) (Pinheiro et al., 2007; Posada and Buckley, 2004)[31].

However, MAgPIE-F simplifies the procedure since a model where slope is allowed to vary for each year, is argued to grasp the between-time trend of observed wood product demand for a defined GDP per capita which is of central interest for demand predictions. Random effects in the intercept or in the slope and intercept together would have been difficult to interprete. The time series inputs (1980 to 2008) for SVP and WF are provided in Appendix B, Figures 2 and

[31] The bigger AIC values get, the higher is the amount of information lost (Posada and Buckley, 2004), i.e. the AIC should be minimized.

3.

Mathematically, the model of estimated per capita consumption $\widehat{Z}$ for historical years T, wood products WP and regions I is derived as

$$
\begin{aligned}
\widehat{Z}_{t,wp,i} =& \alpha_{wp}(t)^2 \\
&+ 2\left(\alpha_{wp}(t)\beta_{wp}\right) gdp_{t,wp,i}^{1/2} \\
&+ \beta_{wp}^2 gdp_{t,wp,i}, for\ wp \in WP\left\{'SVP','WF'\right\},\ \forall\ t \in T,\ \forall\ i \in I
\end{aligned} \tag{2.22}
$$

with gdp denoting the GDP per capita, and $\alpha_{wp}(t)$ the regression coefficient as function of time. The intercept parameter is estimated by $\beta = 0.00342$. α_{wp} has a fixed and a random effect,

$$\alpha_{wp}(t) = \alpha_{wp,r}(t) + \alpha_{wp,f} \tag{2.23}$$

with f and r indicating the fixed and random effects of slope parameter α with $\alpha_f = -0.01099$. The random model of the slope $\alpha_r(t)$ with time as the grouping variable shows a linearly decreasing slope across time:

for $wp =' SVP',\ \forall\ t \in T$

$$\alpha_{wp,r}(t) = 0.003654 - 0.000016\ t \tag{2.24}$$

In contrast to SVP, WF does not show any random effects in the slope parameter α. The trend in the between-time GDP per capita and the pooled regression model is retained for demand projections of WF consumption per capita over GDP per capita.

The results of the mixed effect model fits for SVP are shown in the following plot matrix (Figure 2.20).

The scatterplot of residuals against fitted values should show no pattern (the red smooth curve should not deviate from the dotted line). For the case of SVP, a pattern is observed, which is ascribed to the heteroscedasticity in the errors, i.e. non-constant variances of the residuals. To reduce this problem, a square root transformation of the variables was done. However, the plot also shows that the variation of residuals does not depend on the magnitude of the fitted value. The Normal Quantile-Quantile (Q-Q) plot shows the sorted quantiles of residuals from the Mixed Effect Model fit and assesses how similar the distribution of model residuals is to the theoretically normally distributed residuals. The two distributions are not dissimilar (deviation from the dotted identity line $y = x$ in the upper quantiles which indicates that the model residuals only partly fits the theoretical normal distribution. The Probability Density Function (PDF) plot underpins a partly right-skewed distribution of residuals and higher density around the mean value. The skewness is partly explained by the observed, though reduced, heteroscedasticity (see Figure 2.15) with square root transformed datasets. The correction of the distribution towards normal distribution is not essential for predictions of mean SVP consumption pe capita, since

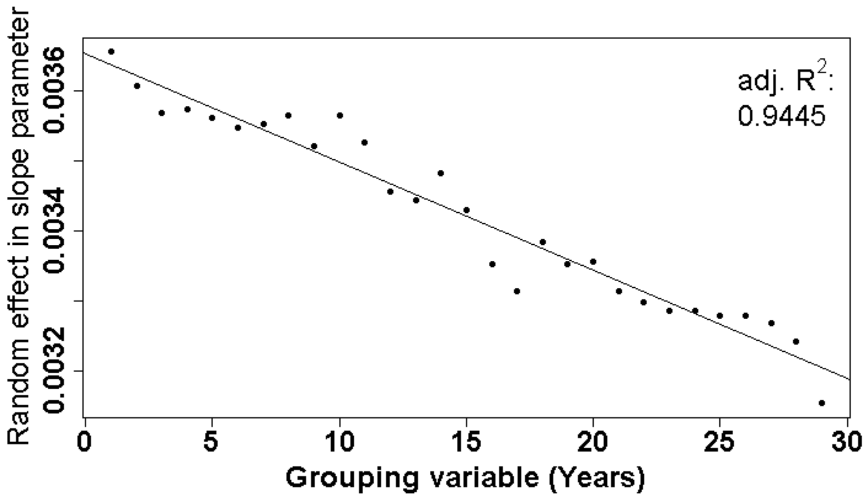

Figure 2.19: Random effect in the slope of predicted SVP consumption per capita as a function of time 1980 - 2008

prediction intervals are not calculated and the distortion of the predicted mean is assumed to be negligible. Therefore, the implementation of variance functions for modelling heteroscedasticty (Pinheiro et al., 2007) is beyond the scope of this thesis and left for future work.

The effect of time on the predicted SVP consumption per capita is illustrated in Figure 2.21 for a horizon of 50 and 100 years versus the model with the fixed effect only.

Post-processing

The consumption of wood products per capita enters MAgPIE-F as a translation into regional derived wood removals per capita in roundwood equivalents. The estimated outputs of the global wood product demand models have been downscaled to regional derived wood removals by regional self-sufficiency shares[32]. A linear calibration function with the intercept defined as the difference between estimated $\widehat{Z}$ and observed Z wood product demand in 1995 (FAO, 2006) has been used with a linearly decreasing slope until 2100.

$$\forall\, wp \in WP,\ \ \forall\, t \in T,\ \ \forall\, i \in I$$

$$\widehat{\delta}_{t,wp,i} = \widehat{Z}_{t,wp,i} - \widehat{Z}_{'1995',wp,i} - Z_{'1995',wp,i} + \frac{\left(\widehat{Z}_{'1995',wp,i} - Z_{'1995',wp,i}\right)}{\sum_{t=1}^{T} t}\, t \tag{2.25}$$

The estimation of the expected derived wood removals in the future follows the procedure of

[32]They denote the sum of country-level domestic production share at apparent consumption for the countries mapped to each region.

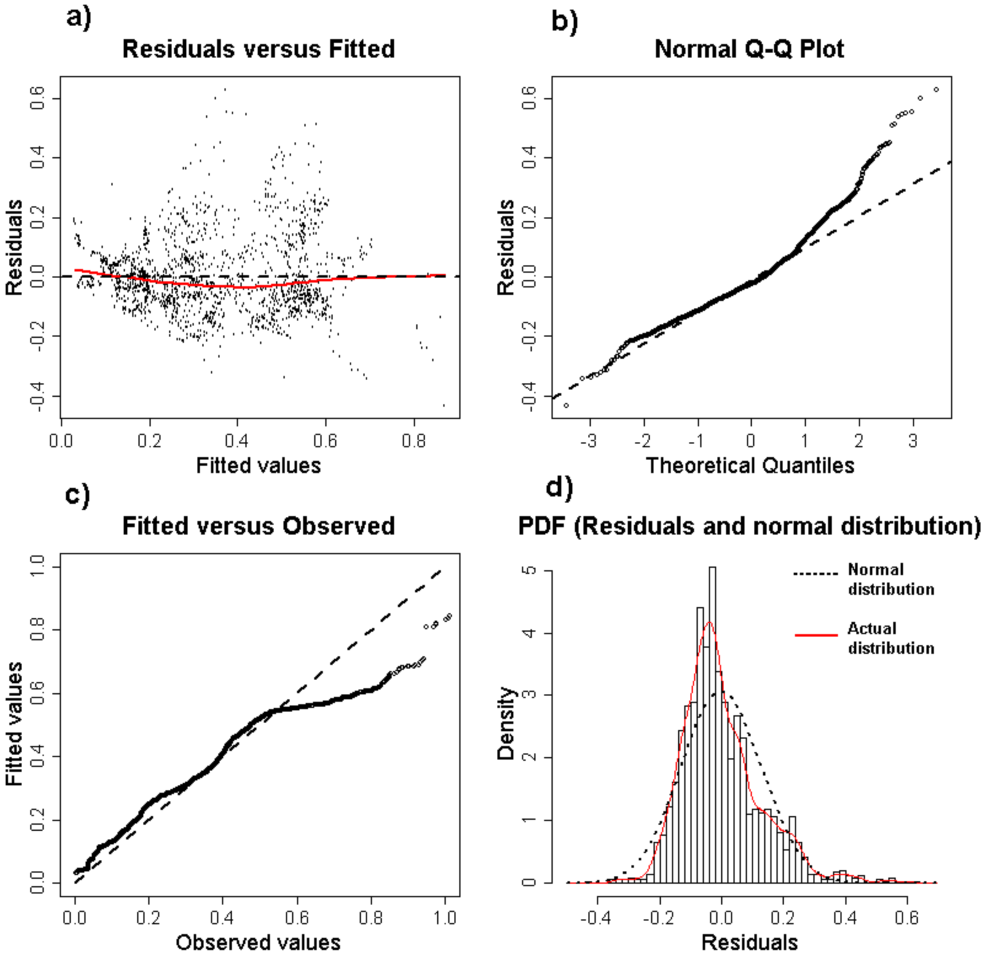

Figure 2.20: Statistical properties of mixed effect model for SVP consumption per capita

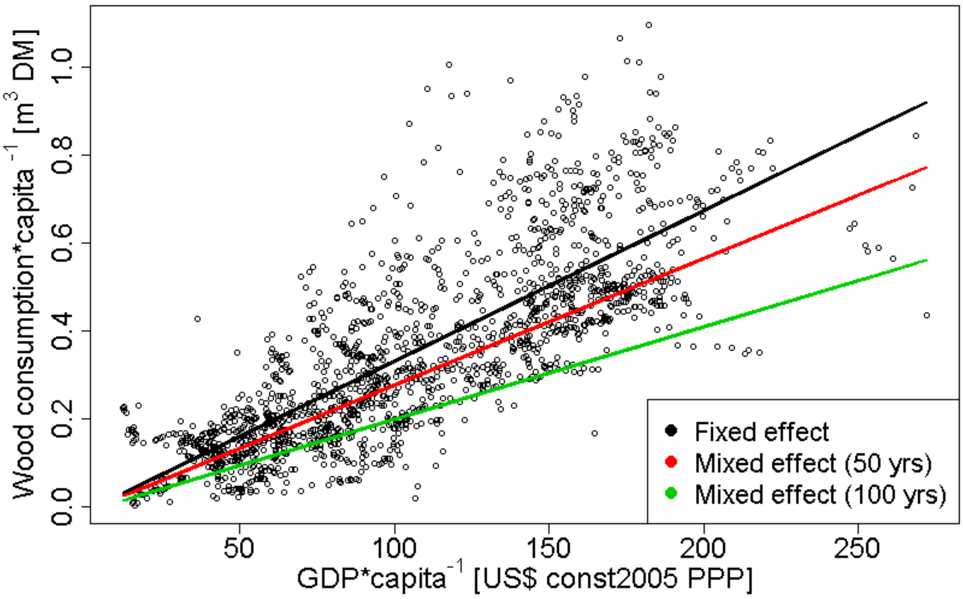

Figure 2.21: Mixed versus fixed effect result of predicted SVP consumption per capita into the future

present wood product demand's translation into present derived wood removals (Subsubsections 2.3.3 and 2.4.2).

2.3.4 Land allocation and additional mechanisms to bring demand and production into equilibrium across time scales

Authors: Michael Krause, Jan Dietrich, Gunner Luderer, Hermann Lotze-Campen, Isabell Weindl

The Subsection deals with the land allocation options, the concepts and implementation in MAgPIE-F as well as the mechanisms of market clearing, i.e. means that bring demand and production into equilibrium in the short (less than one decade) and long (more than one decade) runs.

Land allocation

Land is allocated to agricultural and forestry production activities. The algorithm distinguishes between land allocation

- at the intensive margin between actually managed land types, i.e. cropland, age-class forest and pasture land and
- at the extensive margin from unmanaged land such as undisturbed natural forest or potentially managed land such as other forest and other natural vegetation to managed land.

Furthermore, land is endogenously allocated (throughout the optimization procedure) and partly allocated based on rules in the post-processing procedure after each time step. Endogenous land allocation takes place if land is converted from:

1. cropland to cropland, age-class forest, pasture;
2. age-class forest to age-class forest, cropland, pasture;
3. pasture to cropland, age-class forest;
4. natural forest to cropland, age-class forest, pasture and
5. other natural vegetation to cropland, age-class forest, and pasture.

Land allocation takes place to achieve the reduction of total cross-sectoral production costs. A hectare of currently managed land is kept in agricultural or forestry production based on the relative benefit of not reallocating the hectare of land, which is explained hereafter.

The total production costs are minimized, given constant technological change, land expansion and prescribed consumption quantities, if the marginal product of land per US$ (Hall and Lieberman, 2007) input in agriculture is equal to the marginal product of land per US$ input in forestry. The forestry decision making to take an additional ha of land into account is based on the expected annual cost of production in perpetuity. In agriculture, the expected production cost estimate is revised each decade, in forestry it changes after each forest rotation (see Subsubsection 2.4.2 for mathematical details). The conversion of available unmanaged land to either cropland or age-class forestland additionally takes the costs of land clearing (e.g. removal of stumps, drainage of wetlands) and land conversion (e.g. built-up of necessary infrastructure) into account. If available unmanaged forestland is clearcut, the cost of wood harvesting accrue on top of the cost of land clearing and infrastructure if the harvest of roundwood is an additional goal of forest encroachment. Alternatively, there is no clearcut and forest is burned instead. Then, zero costs of harvest are assumed although the costs of land clearing is still accrued.

The annualized costs of keeping land in forestry are weighted against the annual costs of shifting that hectare of land to agriculture and subsequent agricultural production. Presupposing the scarcity of managed land and given the aforesaid, a greater marginal product of land per US$ in agriculture than in forestry leads to land shifts from forestry to agriculture.

The rule-based allocation of land pertains to spatial clusters (Dietrich, 2011) where, a) more than one natural forest type (forest types III to V) is available for conversion at the extensive margin and b) the endogenously derived demand for natural forestland has to be broken down to potentially managed natural forest and undisturbed natural forest. The rule-based allocation of potentially managed natural forest (forest type III) and undisturbed natural forest (forest types IV and V) to agricultural and forestry production activities per spatial cluster takes place since these forest types are homogenous in yields and the consideration of other cost determinants such as the distance to markets. The rule implies that potentially managed natural forest is used first before undisturbed natural forest gets cut. This assumption is reasonable since the undisturbed natural forest cover class has been derived by means of the wilderness approach (Sanderson et al., 2002; Erb et al., 2007) and is thus less accessible but also considered worth being conserved (Bryant et al., 1997; Brooks et al., 2006; Potapov et al., 2008).

Short and long-term equilibrium of demand and production

There are three major mechanisms implemented in the model to allow production in agriculture and forestry to match the prescribed sectoral demand for commodities. These mechanisms come into play at different time scales for different sectors. In agriculture, the land user's behaviour is characterized as myopic which is inherent to the recursive-dynamic modelling approach and only covers a short-term perspective. There is a technological change that increases agricultural yields at additional costs, there are shifts in rotational constraints, i.e. crop management or the change in trade patterns (Lotze-Campen et al., 2008; Schmitz et al., 2011). In forestry, the land user is partly myopic in a way that future wood production costs do not impact contemporary wood harvest decisions. The range of short-term mechanisms to bring wood production and demand into equilibrium are:

- intensified harvest,
- trade of wood commodities above self-sufficiency rates and
- forest management.

Shifts in wood product demand and derived wood removals respond to intensified wood harvest in mature stands along the marginal harvest cost curve[33]. Thus, the mechanism in MAgPIE-F follows the principle of production shifts if demand shifts by intensified harvest (Bullard and Watson, 1986).

Trade in wood commodities between regions is simulated endogenously, constrained by minimum self-sufficiency rates in each region. This is to say that a minimum level of domestic demand has to be provided within the region, while the rest can be allocated to other regions according to comparative cost advantages.

In the long run, the rationally expected demand for wood commodities in the future has to be met by making production decisions today. The decision maker adjusts the behaviour based on site selection and the magnitude of forest establishment accordingly.

In the long run,

- forest management and,
- uncertainty surcharges in area of forest establishment to cope with unexpected harvest losses

serve to cope with the risk of wood production to demand gaps which may accrue due to unexpected production cost changes in agriculture from technological change, the derived demand for land and the feedback on contemporary wood harvest decisions.

2.4 Mathematical extensions of MAgPIE: Applications excluding and including the forestry sector

This section provides the mathematical description of model modifications complementary to the reference version of MAgPIE which covers the agriculture sector (Lotze-Campen et al., 2008)

[33]Marginal harvest costs are based on spatially-explicit forest growth curves and constant per hectare costs, thus varying per m^3 costs, see Subsection 2.3.2.

and is mathematically described in Appendix A as adapted from (Dietrich, 2011).

First, the reference model has been adapted to investigate the biophysical and economic impacts of forest conservation strategies on the agriculture sector while the forestry sector is not modelled explicitly.

Second, a simple representation of the forestry sector has been implemented to extend studies on biophysical and economic impacts from land use change in different sectors.

Third, climate change mitigation policies to promote AD and additional AR activities have been employed to study the benefits and costs while the derived demand and competition between the agriculture and forestry sectors for land is modelled explicitly.

2.4.1 The conservation of undisturbed natural forest and economic impacts on agriculture

The Subsection explicates the mathematical description supplementary to the model application in Section 3.

Sets

Additional sets to the reference MAgPIE need to be defined.

- $A = \{\text{Available land pools } a\}$: Available land potentially allocated to crop production in addition to already used cropland or forest conservation activities comprises available intact and frontier forest land a_1 and other available land a_2.

Parameters

Several new parameters P_t have been added to those presented in Appendix A.

- $p_{i,a}^{lcc}$: Area-related land conversion costs for each region and each available land pool [US$ / ha].
- p_j^{avland} : Total area of land available for crop production and forest conservation for each cluster [ha].
- $p_{j,a}^{avl}$: Total amount of available land which is potentially convertible to crop production and forest conservation activities in each cluster at initialzation in time step t_0 [ha].
- p_j^{avryld} : Crop area - weighted mean of obtainable agricultural crop yields for each cluster j [ton / ha].
- $p_j^{natvegc}$: Total natural vegetation carbon content for each cluster j [gC / m_2].
- s^{fcons} : Scalar value to switch forest conservation on and off [-].
- s^{fcost} : Scalar value which indicates the start year of forest conservation [-].
- s^{sfac} : Scalar scaling factor to enforce optimization of forest conservation dummy costs prior to agricultural production costs [10^{10}].
- s^{cofac} : Scalar reduction factor to delineate the global forest conservation area, which is varied for different forest conservation scenarios [-].

Variables

The declaration of additional variables becomes neccessary. The land conversion activity is expressed by means of an intermediate variable, which does not generate output for analysis but is needed to track the available land pool for land being converted into cropland.

- $x_{t,j,a}^{lndcon}$: The total area of land allocated from each available land pool a to production activities for each cluster j and each time step t [ha]
- $x_{t,j}^{fcons}$: The total area of land allocated from intact and frontier forest to forest conservation activities for each cluster j and each time step t [ha]

Sub-Functions

The general model structure is simplified by sub-functions which depend on variables. The sub-functions describe the available land area, the forest area conserved at global and regional scale as well as the land conversion costs across time.

The total amount of land available for crop production in each cluster is determined by the potentially convertible land function $f_{t,j,a}^{avl}$ and actually used $x_{t,j,v,w}^{area}$. The potentially convertible land is updated as:

$$f_{t,j,a_1}^{avl}(x_t) = \begin{cases} p_{j,a_1}^{avl} - x_{t,j,a_1}^{lndcon} - x_{t,j}^{fcons} & : t = t_0 \\ f_{t-1,j,a_1}^{avl}(x_t) - x_{t,j,a_1}^{lndcon} - x_{t,j}^{fcons} & : t \geq t_0 \end{cases}, \ \forall\ j \in J,\ \forall\ t \in T \tag{2.26}$$

$\forall\ j \in J,\ \ \forall\ t \in T$

$$f_{t,j,a_2}^{avl}(x_t) = \begin{cases} p_{j,a_2}^{avl} - x_{t,j,a_2}^{lndcon} & : t = t0 \\ f_{t-1,j,a_2}^{avl}(x_t) - x_{t,j,a_2}^{lndcon} & : t \geq t0 \\ \end{cases}$$
$$+ \left(\sum_{v,w} x_{t-1,j,v,w}^{area} - \sum_{v,w} x_{t,j,v,w}^{area} \right) : \left(\sum_{v,w} x_{t-1,j,v,w}^{area} - \sum_{v,w} x_{t,j,v,w}^{area} \right) > 0, t \geq t_0 \tag{2.27}$$

Abandoned cropland is shifted to the other available land pool $f_{t,j,a_2}^{avl}(x_t)$. Even if forest succession happens on this land, emerging (secondary) forest types are entirely distinct from primary natural forest with respect to ecological and economic characteristics and thus kept separated.

The function f_j^{coifff} is depending on the definition of forest conservation scenarios regarding its value as function of time. There are two scenarios, the first one reflects the implementation of forest conservation within a decade and constant magnitude thereafter while the second one allows for gradual increase in conserved area over several decades.

Scenario 1:

$$f_j^{coifff}(x_t) = \begin{cases} f_{t,j,a_1}^{avl}(x_t) s^{cofac} & : t = s^{fcost} \\ 0 & : t \neq s^{fcost} \end{cases} \tag{2.28}$$

Scenario 2:

$$f_j^{coifff}(x_t) = \begin{cases} f_{t=s^{fcost},j,a_1}^{avl}(x_t) s^{cofac} & : t \geq s^{fcost} \\ 0 & : t < s^{fcost} \end{cases} \tag{2.29}$$

The function on the distribution of forest conservation activities across regions is specified as follows.

Scenario 1:

$$f_i^{fdistr}(x_t) = \begin{cases} \sum_{j_i} \frac{f_{t,j,a_1}^{avl}(x_t)}{f_j^{coifff}(x_t)} & : t = s^{fcost} \\ 0 & : t \neq s^{fcost} \end{cases} \tag{2.30}$$

Scenario 2:

$$f_i^{fdistr}(x_t) = \begin{cases} \sum_{j_i} \frac{f_{t=s^{fcost},j,a_1}^{avl}(x_t)}{f_j^{coifff}(x_t)} & : t \geq s^{fcost} \\ 0 & : t < s^{fcost} \end{cases} \tag{2.31}$$

Goal function

Changes in the goal function and constraints are depicted in a condensed form. The goal function has been modified as follows.

$$\begin{aligned} g_t(x_t) = & \sum_{i,v} \left(p_{i,v}^{frv} f_{t,i}^{growth}(x_t) \sum_{j_i,w} x_{t,j,v,w}^{area} \right) \\ & + \sum_{i,l} \left(p_{i,l}^{frl} x_{t,i,l}^{prod}(x_t) \right) \\ & + \sum_{i} \left(p_{i,a}^{lcc} \sum_{j_i} x_{j,a}^{lndcon} \right) \\ & + p^{tcc} \sum_{i} \left(x_{t,i}^{tc} \left(\frac{1}{|V|} \sum_{v} p_{i,v}^{\tau 1} f_{t,i}^{growth}(x_t) \right)^{p^{cxp}} \sum_{j_i,v,w} x_{t-1,j,v,w}^{area} \right) \\ & + \begin{cases} \sum_j \left(x_{t,j}^{fcons} p_j^{avryld} s^{sfac} \right) & : s^{fcons} = 0 \\ \sum_j \left(x_{t,j}^{fcons} (-p_j^{natvegc}) s^{sfac} \right) & : s^{fcons} = 1 \end{cases} \end{aligned} \tag{2.32}$$

The goal function which reduces the total costs of agricultural production has been modified in two ways. First, the last term adds dummy costs of forest conservation[34], which is arguably most beneficial to be regarded in total cost minimization first, since the impact is strongest depending on the scaled magnitude of unit costs. In post-processing, these dummy costs are subtracted from results in order to obtain the agricultural production costs. Second, land conversion costs $p^{lcc}_{i,a}$ have been modified to give priority to other available land conversion over forest conversion by rule. Unit land conversion costs are constant but differ between available land pools. An indiscriminantely small difference in unit land conversion costs $p^{lcc}_{i,a}$ from f^{avl}_{t,j,a_2} to $x^{area}_{t,j,v,w}$ imitates the priority given to available land other than undisturbed natural forest (f^{avl}_{t,j,a_1}) to be converted to cropland. This rule is reasonable since other available land comprises previously abandoned land, too.

Land constraints

During optimization the land constraint of land types, i.e. crop and non-cropland, in each cluster is binding for the sum of crop production and conversion activities. The cropland constraint is modified to incorporate the derived demand for land by the forest conservation activity. The time-independent parameter p^{avland}_j constitutes the total amount of land available for crop production in each cluster, i.e. the sum of f^{avl} and x^{area}. The actual crop production activity in x^{area} which competes with forest conservation f^{coifff} for land in f^{avl}.

$$\sum_{v,w} x^{area}_{t,j,v,w} \leq p^{avland}_j - x^{fcons}_{t,j}, \ \forall\ j \in J, \ \forall\ t \in T \tag{2.33}$$

The forest conservation constraint ensures that the forest conservation activity corresponds to the global forest area to be conserved in conservation scenarios.

$$\sum_{j} x^{fcons}_{t,j} = f^{coifff}_j(x_t), \ \forall\ t \in T \tag{2.34}$$

Further, the global forest conservation area is proportionally distributed among the regions. By this means different forest eocsystem types are covered by forest conservation programmes including associated ecosystem services.

$$\sum_{j_i} x^{fcons}_{t,j} \geq \sum_{j_i} \left(f^{coifff}_j(x_t)\right) f^{fdistr}_i(x_t), \ \forall\ i \in I, \ \forall\ t \in T \tag{2.35}$$

[34]Note, that these are not direct factor market - based costs but costs in terms of foregone agricultural production or natural vegetation carbon storage respectively.

2.4.2 The forestry sector in MAgPIE-F

Hereafter, the forestry sector implementation does not require the stand alone MAgPIE extension 'The conservation of undisturbed natural forest and its economic impacts on agriculture' but partly redefines already used sets, parameters and constraints (Appendix A, based on Dietrich (2011)). Constraints and sub-functions which are unmodified compared to Appendix A are not introduced hereafter. However, the sets of indices, parameters and variables in modified equations are fully introduced for the ease of understanding.

Sets

In MAgPIE-F, a range of sets is defined complementary to the reference MAgPIE.

- $I = \{\text{World regions } i\}$: 10 economic world regions (Lotze-Campen et al., 2008).
- $J = \{\text{Spatial clusters } j\}$: Highest spatial disaggregation level (Dietrich, 2011).
- $TE = \{\text{Time steps } te\}$: Extended set of time steps that covers the simulated time steps T ($TE \supset T$). The expression $te + o$ denotes the time step o after the first time step te. The extended set of time steps is employed to index the transversality condition of the quantity of wood demanded in future. The time step $te + o^{max}$ defines the terminal time step.
- $T(TE) = \{\text{Simulation time steps } t\}$: Simulation time steps ($T \subset TE$), where t denotes the current time step, $t - 1$ the previous time step and so on. The first simulation time step is t_0, $t + n$ is defined as the n-th time step after the current time step t. The time step $t + n^{max}$ defines the final time step of simulation.
- $W = \{\text{Water supply type } w\}$: Comprises rainfed 'rf' and irrigated 'ir' water supply in crop production (Lotze-Campen et al., 2008).
- $K = \{\text{Simulated products } k\}$: Union of vegetal products V and livestock products L KK plus forest products F ($K = KK \cup F : KK = V \cup L$).
- $V = \{\text{Vegetal products } v\}$: Comprises 20 vegetal production activities (Dietrich, 2011).
- $L = \{\text{Livestock products } l\}$: Products simulated within the livestock sector (Dietrich, 2011).
- $F = \{\text{Produced roundwood types } f\}$: Union of aggregated wood production activities in age-class forest FP and non-age-class forest FNP ($F = FP \cup FNP$).
- $FP = \{\text{Produced roundwood types from age-class forest } fp\}$: Softwood 'swd' and hardwood 'hwd' production activities in age-class forest.
- $FNP = \{\text{Produced roundwood types from non-age class forest } fnp\}$: Mixed wood production activities 'mixed' in uneven-aged ('non-age-class') forest, all forests that are not age-class forest. The category 'Mixed' either covers softwood or hardwood production activities depending on the dominant PFT in forest types, which is available from the pre-processing of vegetation carbon stocks but not used in the current study (see Subsubsection 2.3.1).

- $GS = \{$Goods and carbon services from forests $gs\}$: The union of industrial roundwood types, woodfuel, denoted as wood commodities WC, and carbon sequestration and carbon storage services, denoted as CS, is covered ($GS = WC \cup CS$).

- $WC(GS) = \{$Wood commodities $wc\}$: Wood production activities result in the harvest of wood commodities, which are wood raw material classes by FAO (2006), i.e. Saw logs and Veneer logs 'slvl', Pulp logs 'pl', Other industrial roundwood 'oirw.r' and Woodfuel 'wf.r'.

- $WP = \{$Wood products $wp\}$: Wood industry products and forestry end products are employed to derive the demand for wood commodities. They comprise Sawnwood, Veneer sheets, Plywood 'svp', wood pulp 'wpp', Other industrial roundwood 'oirw.e' and Woodfuel 'wf.e' (FAO, 2006).

- $AC = \{$Age classes $ac\}$: 11 decadal age classes are simulated in age-class forest to stem part of wood production $AC = \{ac10...ac110\}$.

- $LP = \{$Land pools $lp\}$: Distinct land pools, which comprise managed land pools M, forest land FT and other natural vegetation NV, $LP = M \cup FT \cup NV$, $A \subset LP$ available land pools for cultivated area expansion A are a subset of LP (see Subsection 2.2.2 and Appendix B, Figure 4).

- $A(LP) = \{$Available land pools $a\}$: Union of available unmanaged land potentially allocated to crop, livestock or forestry production, i.e. natural forest AF and other natural vegetation ANV ($A = AF \cup ANV$).

- $M(LP) = \{$Managed land pools $m\}$: Managed land in crop 'crop' or livestock 'past' production.

- $FT(LP) = \{$Forest land pools $ft\}$: Union of age-class MFT and non-age class NFT forest types ($FT = MFT \cup NFT$). All forest types are used for wood production activities F, (see Appendix B, Figure 4).

- $MFT(LP) = \{$Age-class forest types $mft\}$: Managed forest types, softwood 'swdaf' and hardwood 'hwdaf' age class forest, listed with each distinct age class AC on land that is at least marginally suitable 'si0' for production or not 'nsi0', i.e. $MFT = \{swdaf.ac10.si0...hwdaf.ac110.nsi0\}$. MFT are used in wood production FP.

- $NFT(LP) = \{$Non-age class forest types $nft\}$: Managed 'foth' or unmanaged (undisturbed) 'ifff' natural forest types, on land that is at least marginally suitable 'si0' for production or not, 'nsi0', $NFT = NAF \cup AF$,
i.e. $NFT = \{foth.si0...ifff.nsi0\}$. NFT are used in wood production FNP.

- $NAF(LP) = \{$Non-available non-age class forest types $naf\}$: Not at least margi-nally suitable 'nsi0' land with undisturbed natural forest and other natural forest $NAF = \{ifff.nsi0, foth.nsi0\}$.

- $AF(LP) = \{$Available natural forest land pools $af\}$: At least marginally suitable 'si0' land with undisturbed natural forest and other natural forest $AF = \{ifff.si0, foth.si0\}$.

- $NV(LP) = \{$Other natural vegetation land pools $nv\}$: $NV = NANV \cup ANV$

- $ANV(LP) = \{$Available other natural vegetation land pools $anv\}$: At least marginally suitable 'si0' or complementary 'nsi0' land without forest stocks $ANV = \{natveg.si0, natveg.nsi0\}$.
- $NANV(LP) = \{$Non-available other natural vegetation land pools $nanv\}$: Prepared to contain non-available land defined by rules, currently empty, $NANV = \varnothing$

- $MR(LP) = \{$Receiving managed land pools $mr\}$: Receiving managed land pools after natural forest land conversion for cultivation or clearcut without specific succeeding land use $MR = \{crop.si0, past.si0, past.nsi0\}$.
- $MRS(LP) = \{$Receiving managed land pools at least marginally suitable $mrs\}$: Receiving managed land pools after natural forest land conversion which are at least marginally suitable for crop cultivation $MRS = \{crop.si0, past.si0\}$.
- $MRN(LP) = \{$Receiving managed land pools not at least margi-nally suitable $mrn\}$: Receiving managed land pools after natural forest land conversion not at least marginally suitable for crop cultivation $MRN = \{past.nsi0\}$.
- $HVT = \{$Harvest types $hvt\}$: Wood harvest is either done by clearcut 'cc' or selective logging 'sl' at sustainable harvest level. The distinction is only be made for uneven aged forest in the current model version.

In addition to the mathematical explanation on the variables and domains in MAgPIE (Dietrich, 2011), the forestry sector implementation increases the number of variables and domains. The five additional variables are described in Subsubsection 2.4.2.

$$\begin{aligned}
\Omega^{est} &= \mathbb{R}^{|J|} \times \mathbb{R}^{|FP|} \times \mathbb{R}^{|GS|} \\
\Omega^{hv} &= \mathbb{R}^{|J|} \times \mathbb{R}^{|WC|} \times \mathbb{R}^{|FT|} \times \mathbb{R}^{|HVT|} \\
\Omega^{mfac} &= \mathbb{R}^{|J|} \times \mathbb{R}^{|F|} \\
\Omega^{lndcon} &= \mathbb{R}^{|J|} \times \mathbb{R}^{|A|} \times \mathbb{R}^{|M|} \\
\Omega^{impi} &= \mathbb{R}^{|I|}
\end{aligned}$$

For each timestep, the dimension of the solution space is defined by the number of respective domains as $dim\Omega = |J| \cdot |FP| \cdot |GS| + |J| \cdot |WC| \cdot |FT| \cdot |HVT| + |J| \cdot |A| \cdot |M| + |I|$ and the dimension of $\Omega_T = \Omega \times T$ as $dim\Omega_T = |T| \cdot dim\Omega = |T| \cdot (|J| \cdot |FP| \cdot |GS| + |J| \cdot |WC| \cdot |FT| \cdot |HVT| + |J| \cdot |A| \cdot |M| + |I|)$.

The depiction of parameters and variables uses subscripts which to denote the dimension of the subdomains. Single elements of a set are written in quotes. Superscripts indicate the names of parameters and variables.

Parameters

The definition of parameters for the forestry sector P_t have become necessary analogous to the agriculture sector parameters as documented by Dietrich (2011) and adapted in Appendix A.

- p_i^{aopf} : Observed regional area of planted forest 2000-2010 for each region [ha] (FAO, 2010; Del Lungo et al., 2006).
- $p_{t,j,nft,wc}^{avle}$: Expected area of remaining natural forest in years corresponding to rotation ages for different wood commodities based on historical deforestation trend (FAO, 2010) for each time step, each cluster, each non-age-class forest type and each wood commodity [ha].
- p^{bark} : Bark conversion factor, roundwood under bark to roundwood over bark [% / 100].
- $p_{t,f}^{ctr}$: Transport costs for each time step and each production activity [$US\$_{const2005}$ / km], see Subsection 2.3.2.
- $p_{i,f}^{cwh}$: Wood harvest costs in age-class forests and natural forests for each region and each forest production activity [$US\$_{const2005}$ / ha], see Subsection 2.3.2.
- p^{cxp} : Correlation exponent between τ-Factor and technological change costs [-].
- p_j^{dist} : Transport distance to next urban center for each cluster [min].
- $p_{i,fp}^{frecc}$: Recurrent forest management costs for each region and each age-class forest production activity [$US\$_{const2005}$ / ha], see Subsection 2.3.2.
- $p_{i,fp}^{fregc}$: Forest regeneration costs for each region and each age-class forest production activity [$US\$_{const2005}$ / ha], see Subsection 2.3.2.
- $p_{i,l}^{frl}$: Production related factor requirements for livestock products for each livestock type and each region [US$ / ton].
- $p_{i,v}^{frv}$: Area related factor requirements for each crop and each region based on the technological development level in the initial time step [US$ / ha].
- p^{hvlnac} : Harvest loss factor in non-age class forest, which covers woody biomass residues left in the forest after harvest operation and wood (industrial roundwood and woodfuel) removal [% / 100].
- p_{fp}^{hvlac} : Harvest loss for each production activity in each age class forest type, which covers woody biomass residues left in the forest after harvest operation and wood (industrial roundwood and woodfuel) removal [% / 100].
- p^{int} : Interest rate [% / 100]
- $p_{i,ac,gs}^{mrlac}$: Required minimum rotation length of age-class forest to either produce merchantable roundwood or correspond to common project length in carbon projects for each region, and each good or carbon service (in a vector of boolean values for relevant age classes) [-].
- $p_{t,i,wc}^{pace}$: Expected future share of roundwood production coming from age-class forest for each time step, each region and each wood commodity, which are wood raw materials used to produce wood products [% / 100].

- p^{penalc} : (Dummy) penality costs of increasing imports. They do not constitute real costs but help meeting the wood demand in importing regions by temporarily allowing for increased import activities which triggers additional harvest in export regions in the short run. From the modelling perspective this is required because there may not be sufficient flexibility of adjusting current wood supply to current wood demand from increasing harvest intensity or trade beyond prescribed self-sufficiency rates. Short-term production increases via technological change are not feasible due to longer production horizons than in agriculture. The penality costs per unit are purposively high (10^8) to not distort the optimization procedure because they are not considered as long as less costly means are available to bring regional supply and demand into equilibrium. The penality costs are not counted as model outputs [-].
- p^{sred} : Reduction of the minimum regional area of age-class forest establishment in the future [% / 100].
- p^{ssh} : Prescribed selective logging share per forest area harvested, which does not lead to forest conversion to agricultural land but remains forest land [% / 100].
- $p^{\tau 1}_{i,v}$: τ-Factor representing the agricultural land use intensity in the first simulation time step for each crop in each region [-].
- p^{tcc} : Technological change cost factor accounting for interest rate, expected lifetime and general costs [US$ / ha].
- p^{trbred}_{t} : Factor to reduce the prescribed regional production in the current trade balance for each time step [% / 100].
- $p^{trec}_{i,wc}$: Age of forest when recurrent forest management measures are taken for each region and each wood commodity [years].
- $p^{trl}_{i,gs}$: Forest rotation length for each region and each wood commodity or carbon service [years].
- p^{uncert} : Expected production surcharge to cover uncertainty over time [% / 100].
- $p^{wcss}_{i,wc}$: Self-sufficiency rate for each region and wood commodity [% / 100], see Subsection 2.3.3.
- $p^{wpd}_{t,i,wp}$: Derived roundwood demand for each time step, each region and wood product [m^3 DM], see Subsection 2.3.3.
- $p^{wpde}_{t,i,wp}$: Expected derived roundwood demand for each time step, each region and wood product [m^3 DM], see Subsection 2.3.3.
- $p^{wpss}_{i,wp}$: Self-sufficiency rate for each region and each wood product [% / 100], see Subsection 2.3.3.
- $p^{yldac}_{j,fp,ac}$: LPJ obtainable yields from harvest of growing stock for each cluster, each production activity in each age-class forest type and each age class [m^3 DM / ha]. The LPJ obtainable yields are calibrated to the area-weighted average country-level growing stocks observed in planted forests at harvest age (Del Lungo et al., 2006), see Subsection 2.3.1.

- $p^{yldace}_{j,fp,gs}$: Expected future LPJ obtainable yields from harvest of growing stock for each cluster, each production activity in each age-class forest type and each good or carbon service in age classes where the age class has reached the minimum rotation length for each good or carbon service provided [m^3 DM / ha], see Subsection 2.3.1.
- $p^{yldnac}_{j,fnp,hvt}$: LPJ obtainable yields from harvest of growing stock for each cluster, each production activity in each non-age-class forest type, and each harvest type [m^3 DM / ha], see Subsection 2.3.1.

Variables

MAgPIE originally defines three variables $x^{area}_t \in \Omega^{area}$, $x^{prod}_t \in \Omega^{prod}$ and $x^{tc}_t \in \Omega^{tc}$ (Appendix A). MAgPIE-F adds $x^{est}_t \in \Omega^{est}$, $x^{hv}_t \in \Omega^{hv}$, $x^{mfac}_t \in \Omega^{mfac}$, $x^{lndcon}_t \in \Omega^{lndcon}$, $x^{impi}_t \in \Omega^{impi}$.

A subset of these variables are employed in the modified equations hereafter.

- $x^{area}_{t,j,v,w}$: Crop production area for each cluster and each time step [ha].
- $x^{est}_{t,j,fp,gs}$: Forest establishment activity in age-class forestry production activities for each wood commodity or carbon service in production activity fp, each cluster and each time step [ha].
- $x^{hv}_{t,j,wc,ft,hvt}$: Wood harvest activity for wood commodities in forest types via harvest methods for each cluster and each time step [ha].
- $x^{impi}_{t,i}$: Factor that reduces the wood self-sufficiency rate in each time step to cope with shortage in domestic wood supply in each region [-].
- $x^{lndcon}_{t,j,a,m}$: The total area of land allocated from each available land pool a to production activities in managed land pools m for each cluster and each time step [ha].
- $x^{mfac}_{t,j,f}$: Management bundle factor that scales yields and factor costs per ha per cluster and region in each production activity f for each cluster and each time step. [-].

Sub-Functions

MAgPIE-F follows the terminology of Appendix A to define sub-functions, whereas demand as function of time is included.

- $f^{dem}_{t,i,wc}(x_t)$: Derived demand for each wood commodity, each region and each time step [m^3 DM o.b.]

The derived demand for wood commodities wc is estimated for each current and future time step, $\forall\ t \in T,\ \forall\ t+n \in T$.

For each current time step, the derived demand for wood commodities is equal to the prescribed derived wood removals in roundwood equivalents per region.

$$f^{dem}_{t,i,wc}(x_t) = f^{wrem}_{t,i,wc}(x_t),\ \forall\ wc \in WC,\ \forall\ i \in I,\ \forall\ t \in T \tag{2.36}$$

- $f^{wrem}_{t,i,wc}(x_t)$: Derived wood removals for each wood commodity, each region and each time step [m^3 DM o.b.]

The derived wood removals in roundwood equivalents per region is a function of the consumed quantity of wood products in roundwood equivalents.

$\forall\ wc \in WC,\ \forall\ i \in I,\ \forall\ t \in T$

$$f^{wrem}_{t,i,wc}(x_t) = \sum_{wp} \left(p^{wpd}_{t,i,wp} p^{wpss}_{i,wp} \right) p^{wcss}_{i,wc} (1 + p^{bark})$$
$$: wp_{1...c} \times wc_{1...d} \in [PC], wp_{1...c} \times wc_{1...d} \neq 0 \tag{2.37}$$

The condition $wp_{1...c} \times wc_{1...d} \in [PC]$ denotes the boolean combination of $wp \in WP\{wp_1...wp_c\}$ and $wc \in WC\{wc_1...wc_d\}$ in the matrix $[PC]$ which is required to hold non-zero value.

- $f^{deme}_{te,i,wc}(x_{te})$: Expected future derived demand for each wood commodity, each region and each time step [m^3 DM o.b.]

Analogously, the future derived demand for wood commodities is equal to the prescribed expected derived gross removals of wood commodities in roundwood equivalents per region for each extended future time step $te + o$. The future time steps $te + o$ are defined by the minimum rotation length required to produce age-class specific quantities of each wood commodity.

$$f^{deme}_{te,i,wc}(x_{te}) = f^{wreme}_{te,i,wc}(x_{te}),\ \forall\ wc \in WC,\ \forall\ i \in I,\ \forall\ te + o \in TE \tag{2.38}$$

- $f^{wreme}_{te,i,wc}(x_t)$: Expected future derived wood removals for each wood commodity wc, in each region i and each time step te [m^3 DM o.b.]

The expected future derived wood removals are defined at the minimum rotation length to produce each wood commodity. The estimation includes the transversality condition, i.e. the terminal condition for the stock of derived wood removals.

$\forall\ wc \in WC,\ \forall\ i \in I,\ \forall\ te + o \in TE$

$$f^{wreme}_{te,i,wc}(x_{te}) = \begin{cases} \sum_{wp} \left(p^{wpde}_{te,i,wp} p^{wpss}_{i,wp} \right) p^{wcss}_{i,wc} (1 + p^{bark}) \\ : te \leq t + n^{max}, te \leq te + o^{max} \\ \sum_{wp} \left(f^{wptrs}_{te=t+n^{max},i,wp}(x_{te}) p^{wpss}_{i,wp} \right) p^{wcss}_{i,wc} (1 + p^{bark}) \\ : te > t + n^{max}, te \leq te + o^{max} \end{cases} \tag{2.39}$$

with

$$f^{wptrs}_{te,i,wp}(x_{te}) = p^{wpde}_{te=t+n^{max},i,wp} \tag{2.40}$$

- $f^{wremec}_{te,i,wc}(x_t)$: Expected future derived wood removals for each wood commodity wc, each region i and each time step te based on the current time step t [m^3 DM o.b.]

The expected future derived wood removals are updated in each current time step of simulation t

$$f^{wremec}_{t,i,wc}(x_t) = f^{wreme}_{te,i,wc}(x_{te}) : te = t + n, \ \forall \ wc \in WC, \ \forall \ i \in I, \ \forall \ te + o \in TE \tag{2.41}$$

with n being the number of time steps corresponding to the wood commodity and region specific minimum rotation length.

See Subsection 2.3.3 for more details on datasets employed and statistical models built.

- $f^{fprod}_{t,j,wc}(x_t)$: Wood commodity production activity for each wood commodity wc, each cluster j and each time step t [m^3 DM o.b.]

The production of wood commodities takes place in natural forest and age-class forest.

$$f^{fprod}_{t,j,wc}(x_t) = f^{prodr}_{t,j,wc}(x_t) + f^{prodac}_{t,j,wc}(x_t), \ \forall \ j \in J, \ \forall \ t \in T \tag{2.42}$$

with

$$f^{prodr}_{t,j,wc}(x_t) = \sum_{hvt,fnp_{nft}} \left(x^{hv}_{t,j,wc,nft,hvt} p^{yldnac}_{j,fnp,hvt} \right) \left(1 - p^{hvlnac} \right) \tag{2.43}$$

and

$$f^{prodac}_{t,j,wc}(x_t) = \sum_{hvt,ac_{mft},fp_{mft}} \left(x^{hv}_{t,j,wc,mft,hvt} p^{yldac}_{j,fp,ac} \left(1 - p^{hvlac} \right) \left(1 + x^{mfac}_{t,j,fp} \right) p^{mrlac}_{i,ac,wc} \right) \tag{2.44}$$

- $f^{avl}_{t,j,lp}(x_t)$: Area of land pools lp for each cluster j and each time step t [ha]

The available land pools are updated in the post-processing in each time step $t-1$, do not influence the optimization output in $t-1$, and serve as input in t.

$$f^{avl}_{t,j,af}(x_t) = f^{avl}_{t-1,j,af}(x_t) - \sum_{m} \left(x^{lndcon}_{t-1,j,af,m} \right), \ \forall \ af \in AF, \ \forall \ j \in J, \ \forall \ t \in T \tag{2.45}$$

$$f^{avl}_{t,j,anv}(x_t) = f^{avl}_{t-1,j,anv}(x_t) - \sum_{m} \left(x^{lndcon}_{t-1,j,anv,m} \right), \ \forall \ anv \in ANV, \ \forall \ j \in J, \ \forall \ t \in T \tag{2.46}$$

- $f^{cann}_{t,j,fp,wc}(x_t)$: Annuity cost of future wood production in age class forest for each wood commodity wc, each cluster j and each time step t [US$]

The annuity costs of future wood production f^{cann} are expressed as the present value of future costs in perpetuity (V_{t0}) times the interest rate r,

$$f^{cann} = V_{t0} r \tag{2.47}$$

which translates into

$$\begin{aligned}
f^{cann}_{t,j,fp,wc}(x_t) = \Bigg[\Big\{ & x^{est}_{t,j,fp,wc} p^{chv}_{i,fp} \left(1 + x^{mfac}_{t,j,fp}\right) \\
& + x^{est}_{t,j,fp,wc} p^{yldace}_{j,fp,wc} \left(1 - p^{hvlac}_{fp}\right) \left(1 + x^{mfac}_{t,j,fp}\right) p^{dist}_{j} p^{ctr}_{t,f} \\
& + \left(x^{est}_{t,j,fp,wc} p^{fregc}_{i,fp} (1 + x^{mfac}_{t,j,fp})(1 + p^{int}) \right)^{p^{trl}_{i,wc}} \\
& + \left(x^{est}_{t,j,fp,wc} p^{frecc}_{i,fp} (1 + x^{mfac}_{t,j,fp})(1 + p^{int}) \right)^{(p^{trl}_{i,wc} - p^{trec}_{i,wc})} \Big\} \\
& / \left((1 + p^{int})^{(p^{trl}_{i,wc})} - 1 \right) \Bigg] p^{int}
\end{aligned} \tag{2.48}$$

Goal function

The goal function of MAgPIE-F comprises agricultural and forestry production cost terms.

$$\begin{aligned}
\text{minimize } g_t(x_t) = & \sum_{i,v} \left(p^{frv}_{i,v} f^{growth}_{t,i}(x_t) \sum_{j_i,w} x^{area}_{t,j,v,w} \right) \\
& + \sum_{i,l} \left(p^{frl}_{i,l} x^{prod}_{t,i,l}(x_t) \right) \\
& + p^{tcc} \sum_{i} \left(x^{tc}_{t,i} \left(\frac{1}{|V|} \sum_{v} p^{\tau 1}_{i,v} f^{growth}_{t,i}(x_t) \right)^{p^{cxp}} \sum_{j_i,v,w} x^{area}_{t-1,j,v,w} \right) \\
& + \sum_{i} \sum_{a} \left(p^{lcc}_{i,a} \left(\sum_{j_i,m} x^{lndcon}_{t,j,a,m} + \sum_{j_i,wc,nft} x^{hv}_{t,j,wc,nft,'cc'} \right) \right) \\
& + \sum_{i} \sum_{f_{ft}} p^{cwh}_{i,f_{ft}} \sum_{j_i,wc,ft,hvt} \left(x^{hv}_{t,j,wc,ft,hvt} \right) \left\{ (1 + x^{mfac}_{t,j,f}) : fp \subset f \right. \\
& + \sum_{j,f,wc} \left(f^{fprod}_{t,j,wc}(x_t) p^{dist}_{j} p^{ctr}_{t,f} \right) \\
& + \sum_{j,fp,wc} \left(f^{cann}_{j,fp,wc}(x_t) \right) \\
& + \sum_{i} \left(x^{impi}_{t,i} \right) p^{penalc}
\end{aligned} \tag{2.49}$$

The land conversion costs are depreciated in 10 years. Clearcutting natural forest is also associated with land conversion costs. The total costs of transporting wood commodities WC from the forest road to the market center (saw mills, pulp mills) have been approximated by those derived for agricultural crops. This tentative solution hinders employing the full potential of von Thuenen's location rent approach. In cost minimization terms, the intraregional spatial arrangement of agricultural and wood commodities is in line with the transport cost gradient on top of production costs due to the distance to market centers. The detailed transport cost estimation is left for future modelling work.

The annuity costs of future wood production (harvest) f^{cann} represent an annual equal flow of costs comparable to the annual agricultural production costs. The calculation follows the classical Faustmann formula (Faustmann, 1995; Straka and Bullard, 1996) with the exception that the revenue stream is not accounted for explicitly in cost minimization but the shadow price of wood harvested in the future is a model output. It is assumed that transport costs accrue for inputs in the regeneration phase and for outputs in the harvest phase. The management bundle factor scales expected yields in the range of 10 % (e.g. through modified planting density, pest management, pruning, non-commercial thinning). The increase in expected yield by the management bundle decreases expected harvest costs per m^3 in the future, but is associated with increased costs for forest management at present. The assumption is taken that a linear relationship does exist between the present and future cost change and the expected yield change in the future. All management bundle components are to be paid upon the start of a programme.

Global wood supply and demand balance

The global constraints in the standard MAgPIE version (Dietrich, 2011) are supplemented by the global wood supply and demand balance to ensure global wood market closure.

$$\sum_{j} f^{fprod}_{t,j,wc}(x_t) \geq \sum_{i} f^{dem}_{t,i,wc}(x_t), \ \forall \ wc \in WC, \ \forall \ t \in T \tag{2.50}$$

The common equality constraint to represent market closure has been substituted by an inequality constraint to facilitate feasible model solutions. The challenge of equality constraints in non-linear optimization problems is that a point lies exactly on a curved surface in a multidimensional space which is difficult to meet (Chinneck, 2006). The global excess wood production (production minus demand of wood products) is a model output which indicates the deviation of global wood supply and demand to be smaller than 10^{-10} units.

Regional current wood trade balance

The current wood trade balance equates the regional production to the derived wood removals whilst trade takes place for quantities above historical self-sufficiency shares. On the one hand, the reduction of the required domestic production in the trade balance imitates the stepwise liberalization of wood trade until 2050 and is kept constant thereafter. On the other hand, the trade balance allows for the increase in regional imports if the regional wood production capacity and the current imports are insufficient to cover derived wood removals at given self-sufficiency rates.

$$\sum_{j_i} f^{fprod}_{t,j,wc}(x_t) \geq f^{wrem}_{t,i,wc}(x_t) p^{trbred}_{t} (1 - x^{impi}_{t,i}), \ \forall \ wc \in WC, \ \forall \ i \in I, \ \forall \ t \in T \tag{2.51}$$

Regional future wood trade balance

The required additional production established in the current time step t to meet the future derived wood removals in $te + 1$ is expressed as:

$\forall\ wc \in WC,\ \ \forall\ i \in I,\ \ \forall\ t \in T$

$$\sum_{j_i,fp}\left(x^{est}_{t,j,fp,wc}p^{yldace}_{j,fp,wc}(1-p^{uncert})\right) \geq \begin{cases}\left(f^{wremec}_{t,i,wc}(x_t)p^{pace}_{t,i,wc}p^{trbred}_t\right) \\ :\sum_{j_i,fnp_{nft}}p^{avle}_{t,j,nft,wc}p^{yldnac}_{j,fnp,'cc'} \geq f^{wremec}_{t,i,wc}(x_t)(1-p^{pace}_{t,i,wc})p^{trbred}_t \\ \left(f^{wremec}_{t,i,wc}(x_t)p^{trbred}_t\right) \\ :\sum_{j_i,fnp_{nft}}p^{avle}_{t,j,nft,wc}p^{yldnac}_{j,fnp,'cc'} < f^{wremec}_{t,i,wc}(x_t)(1-p^{pace}_{t,i,wc})p^{trbred}_t\end{cases} \tag{2.52}$$

Wood producers expect the future trade balance to be equal to the current trade balance, independent of the scenario of projected actual wood trade liberalization. The future production and demand is estimated at commodity-specific rotation lengths, the minimum age class to produce merchantable commodities. In MAgPIE-F, the forests are not commodity-specific in the year of model initialization, which is due to missing observed data on specific uses of initialized forests.

Regional sustainable wood harvest constraint

The regional area of selectively logged natural forest is prescribed as minimum constraint by the regional minimum area of sustainably harvested natural forest by selective logging.

$$\sum_{j_i,wc,nft}\left(x^{hv}_{t,j,wc,nft,'sl'}\right) \geq \sum_{j_i,nft} f^{avl}_{t,j,nft}(x_t)p^{ssh},\ \forall\ i \in I,\ \forall\ t \in T \tag{2.53}$$

Regional AR constraint

The observed regional area of planted forest per year (FAO, 2010; Del Lungo et al., 2006) sets the minimum area of age-class forest area established annually. The constraint is relaxed by a parameter on the reduction of the minimum AR area over time p^{sred}. The future trade balance sets the minimum age-class forest area needed to fulfill future demand, given the land productivities.

$$\sum_{j_i,fp,wc} x^{est}_{t,j,fp,wc} \geq \begin{cases} p^{aopf}_i : t < t_3 \\ \left(p^{aopf}_i p^{sred}\right) : t \geq t_3 \end{cases},\ \forall\ i \in I,\ \forall\ t \in T \tag{2.54}$$

Local land conversion constraints

$$x^{lndcon}_{t,j,a,'crop'} \leq \sum_m x^{lndcon}_{t,j,a,m},\ \forall\ a \in A,\ \forall\ j \in J,\ \forall\ t \in T \tag{2.55}$$

The land conversion to cropland is restricted to at least marginally suitable land for crop cultivation, whilst forestry production takes place on other productive sites (see Subsection 2.2.2).

Following this rule, the natural forest area available for land conversion to cropland is restricted to at least marginally suitable land (van Velthuizen, 2007) stocked with intact and frontier forest which is defined as undisturbed natural forest and other natural forest, that is potentially managed, subsumed under af.

$$x^{lndcon}_{t,j,'forest','crop'} \leq \sum_{af} f^{avl}_{t,j,af}(x_t),\ \forall\ j \in J,\ \forall\ t \in T \tag{2.56}$$

The land covered by other natural vegetation which is not forest is also converted to cropland if at least marginally suitable for crop cultivation,

$$x^{lndcon}_{t,j,'natveg','crop'} \leq f^{avl}_{t,j,anv}(x_t) :' natveg.nsi0' \notin anv,\ \forall\ j \in J,\ \forall\ t \in T \tag{2.57}$$

but comprises additional area for forestry:

$$\sum_{mr} x^{lndcon}_{t,j,'natveg',mr} \leq \sum_{anv} f^{avl}_{t,j,anv}(x_t),\ \forall\ j \in J,\ \forall\ t \in T \tag{2.58}$$

Local land constraints

- Managed land demand and supply constraints

The area for age-class forest establishment and current agricultural area have to be equal to or smaller than the available agricultural area and natural forest area converted to managed land and available other natural vegetation area converted to managed land. Previously harvested natural forest area is shifted to grazing land in the postprocessing after optimization in each time step. 'Grazing land' constitutes the managed land pool available in the next time step for land reallocation. Therefore, 1) the land conversion of natural forest after clearcut x^{lndcon} shifts land of natural forest directly to cropland or age-class forest but 2) the harvest activity x^{hv} is not related to a specific subsequent type of land use and thus shifts land of natural forest to grazing before it is available for cropland or age-class forest use in the succeeding time step.

$$\sum_{v,w} x^{area}_{t,j,v,w} + \sum_{fp,wc} x^{est}_{t,j,fp,wc} \leq \sum_{mr} f^{avl}_{t,j,mr}(x_t) + \sum_{a,mr} x^{lndcon}_{t,j,a,mr},\ \forall\ j \in J,\ \forall\ t \in T \tag{2.59}$$

Agricultural crop cultivation is restricted to land that is at least marginally suitable.

$$\sum_{v,w} x^{area}_{t,j,v,w} \leq \sum_{mrs} f^{avl}_{t,j,mrs}(x_t) + \sum_{a} x^{lndcon}_{t,j,a,'crop'},\ \forall\ j \in J,\ \forall\ t \in T \tag{2.60}$$

$$\sum_{fp,wc} x^{est}_{t,j,fp,wc} \geq \sum_{m} \left(x^{lndcon}_{t,j,'forest',m}\right) - x^{lndcon}_{t,j,'forest','crop'},\ \forall\ j \in J,\ \forall\ t \in T \tag{2.61}$$

The age-class forest land demand and supply constraint can be written as follows:

$$\sum_{wc} x^{hv}_{t,j,wc,mft,'cc'} \leq f^{avl}_{t,j,mft}(x_t),\ \forall\ mft \in MFT,\ \forall\ j \in J,\ \forall\ t \in T \tag{2.62}$$

- Natural forest land demand and supply constraint

$$\sum_{wc,nft,hvt} x^{hv}_{t,j,wc,nft,hvt} + \sum_{m} x^{lndcon}_{t,j,'forest',m} \leq \sum_{af} f^{avl}_{t,j,af}(x_t),\ \forall\ j \in J,\ \forall\ t \in T \tag{2.63}$$

2.4.3 The economic potential of market-based climate change mitigation in forests and impacts on agriculture and forestry

The Subsection explicates the supplementary mathematical description to the description in Subsection 2.4.2 which applies to modifications in MAgPIE-F for the study in Section 4.

Sets

- $FCV = \{\text{Options of forest carbon valuation} fcv\}$: Forest carbon valuation scenario, i.e. avoided deforestation 'ad' or afforestation / reforestation ar, $FCV = \{ad, ar\}$.
- $CF(MFT) = \{\text{Carbon forest pools } cf\}$: Subset of age-class forest types ($CF \in MFT$). Carbon forest is used for wood production activities F after a predefined rotation length.

Parameters

- p^{sfcv}_{fcv} : Forest carbon valuation option which is selected for different climate change mitigation scenarios [-].
- $p^{vegc}_{j,fnp,hvt}$: LPJ-derived carbon density from wood production activities in non-age-class forest [tC / ha] (Subsection 2.3.1).
- s^{cc} : Scalar value on carbon to CO_2 conversion (Atomic weight CO_2: 44, atomic weight carbon: 12) [gCO_2 / gC]
- $p^{cac}_{t,i}$: Carbon price for each region and each time step [US$const2005 / t$CO_2$]
- p^{convcf}_{t} : Maximum share of available land converted into carbon forest for each time step [% / 100]

Variables

- $x^{hvcar}_{t,j,wc,ft,hvt}$: Wood harvest activity for wood commodities in carbon forest after a predefined carbon forest rotation length for each cluster and each time step [ha].

Sub-Functions

The wood production activity is expanded to the regular harvest of age-class forest and carbon forest at the end of the rotation length.

$$f^{prodac}_{t,j,wc}(x_t) = \sum_{hvt,ac_{mft},fp_{mft}} \left(p^{yldac}_{j,fp,ac} p^{mrlac}_{i,ac,wc} \left(1 - p^{hvlac}\right) \left(1 + x^{mfac}_{t,j,fp}\right)\right)$$
$$\begin{cases} x^{hv}_{t,j,wc,mft,'cc'} :' ar' \notin fcv \\ \left(x^{hvcar}_{j_i,wc,mft,'cc'} p^{mrlac}_{i,ac,cs}\right) :' ar' \in fcv \end{cases} \tag{2.64}$$

- $f^{cannc}_{t,j,fp,cs}(x_t)$: Annuity cost of future provision of carbon services cs in age-class forests for each cluster j and each time step t [US$]

The annuity costs of future wood production from carbon forests f^{cannc} are expressed as the present value of future costs in perpetuity (V_{t0}) times the interest rate r,

$$f^{cannc} = V_{t0} r \tag{2.65}$$

which translates into

$$\begin{aligned} f^{cannc}_{t,j,fp,cs}(x_t) = & \Bigg[\Big\{ x^{est}_{t,j,fp,cs} p^{chv}_{i,fp} \left(1 + x^{mfac}_{t,j,fp}\right) \\ & + x^{est}_{t,j,fp,cs} p^{yldace}_{j,fp,cs} \left(1 - p^{hvlac}_{fp}\right) \left(1 + x^{mfac}_{t,j,fp}\right) p^{dist}_{j} p^{ctr}_{t,f} \\ & + \left(x^{est}_{t,j,fp,cs} p^{fregc}_{i,fp} (1 + x^{mfac}_{t,j,fp})(1 + p^{int}) \right)^{p^{trl}_{i,cs}} \\ & + \left(x^{est}_{t,j,fp,cs} p^{frecc}_{i,fp} (1 + x^{mfac}_{t,j,fp})(1 + p^{int}) \right)^{(p^{trl}_{i,cs} - p^{trec}_{i,wc})} \Big\} \\ & \left((1 + p^{int})^{(p^{trl}_{i,cs})} - 1 \right) \Bigg] p^{int} \end{aligned} \tag{2.66}$$

Goal function

The scenario application of MAgPIE-F requires appending a scenario-specific term in the goal function. Modelling AD of natural forests may be achieved by pricing forest carbon which increases the value of standing natural forest. In cost minimization of MAgPIE-F, the value of natural forests is not explicitly modelled but forest carbon value from AD enters as opportunity costs on top of conversion costs from natural forest to agriculture or forestry. Opportunity costs are decisive in natural forest conversion but are not accounted for in total sectoral cost calculation.

$$
\begin{aligned}
\text{minimize } g_t(x_t) = & \sum_{i,v} \left(p^{frv}_{i,v} f^{growth}_{t,i}(x_t) \sum_{j_i,w} x^{area}_{t,j,v,w} \right) \\
& + \sum_{i,l} \left(p^{frl}_{i,l} x^{prod}_{t,i,l}(x_t) \right) \\
& + p^{tcc} \sum_{i} \left(x^{tc}_{t,i} \left(\frac{1}{|V|} \sum_{v} p^{\tau 1}_{i,v} f^{growth}_{t,i}(x_t) \right)^{p^{cxp}} \sum_{j_i,v,w} x^{area}_{t-1,j,v,w} \right) \\
& + \sum_{i} \sum_{a} \left(p^{lcc}_{i,a} \left(\sum_{j_i,m} x^{lndcon}_{t,j,a,m} + \sum_{j_i,wc,nft} x^{hv}_{t,j,wc,nft,'cc'} \right) \right) \\
& + \sum_{i} \sum_{f_{ft}} p^{cwh}_{i,f_{ft}} \sum_{j_i,wc,ft,hvt} \left(x^{hv}_{t,j,wc,ft,hvt} + x^{hvcar}_{j,wc,ft,'cc'} \right) \left\{ (1 + x^{mfac}_{t,j,f}) : fp \subset f \right. \\
& + \sum_{j,f,wc} \left(f^{fprod}_{t,j,wc}(x_t) p^{dist}_{j} p^{ctr}_{t,f} \right) \\
& + \sum_{j,fp,wc} \left(f^{cann}_{j,fp,wc}(x_t) \right) \\
& + \sum_{i} \left(x^{impi}_{t,i} \right) p^{penalc} \\
& + \begin{cases} \sum_i p^{cac}_{t,i} \sum_{j_i,wc,a,m} \left(\left(x^{hv}_{t,j,wc,nft,'cc'} + x^{lndcon}_{t,j,a,m} \right) \sum_{fnp} p^{vegc}_{j,fnp,'cc'} s^{cc} \right) : p^{sfcv}_{'ad'} \\ \sum_{j,fp,cs} \left(f^{cannc}_{t,j,fp,cs}(x_t) \right) : p^{sfcv}_{'ar'} \end{cases}
\end{aligned}
\tag{2.67}
$$

Local carbon forest land constraints

$$
\sum_{fp,cs} x^{est}_{t,j,fp,cs} \leq \sum_{mr} f^{avl}_{t,j,mr}(x_t) + \sum_{a,mr} \left(x^{lndcon}_{t,j,a,mr} p^{convcf}_{t} \right), \ \forall \ j \in J, \ \forall \ t \in T \tag{2.68}
$$

p^{convcf} denotes the maximum share of land converted into carbon forest which prevents that the entire available land area per cluster and time step is allocated to carbon forests. The parameter covers constraints like restricting policies for land use planning, other institutional constraints and other obstacles not covered in this model version.

$$
\sum_{wc} \left(x^{hv}_{t,j,wc,mft,'cc'} + x^{hvcar}_{j,wc,mft,'cc'} \right) \leq f^{avl}_{t,j,mft}(x_t), \ \forall \ mft \in MFT, \ \forall \ j \in J, \ \forall \ t \in T \tag{2.69}
$$

$$
\sum_{wc} x^{hvcar}_{j,wc,cf,'cc'} \leq f^{avl}_{t,j,cf}(x_t), \ \forall \ cf \in CF, \ \forall \ j \in J, \ \forall \ t \in T \tag{2.70}
$$

3 Conservation of undisturbed natural forest and economic impacts on agriculture

Authors: Michael Krause, Hermann Lotze-Campen, Alexander Popp, Jan-Philipp Dietrich, Markus Bonsch

3.1 Abstract

Conservation of undisturbed natural forests, which are important for biodiversity, carbon storage, and other ecosystem services, affects agricultural production and cropland expansion. We analyze the economic impacts of undisturbed natural forest conservation programmes on agriculture and the magnitude of avoided deforestation and avoided carbon emissions in the Tropics.

We apply a global agricultural land use model to estimate changes in agricultural production costs for the period 2015 to 2055. Our forest conservation scenarios reflect two different policy goals: either maximize forest carbon storage or minimize impacts on agricultural production. In all the scenarios, the economic impacts on agriculture are relatively low.

The results show that production costs would increase due to forest conservation by a maximum of 4 %, predominantly driven by increased investments in agricultural productivity increase. We also show regional differences in Latin America, Sub-Saharan Africa, and Southeast Asia, due to different growth rates in food demand, land availability and crop productivity. The area of avoided deforestation does not exceed 1.5 million hectares per year in the period 2015 to 2055, while avoided carbon emissions reach a maximum of 1.9 Gigatons CO_2 per year. According to our results on the potential changes in agricultural production costs, undisturbed natural forest conservation appears to be a low-cost option for greenhouse gas emission reduction.

3.2 Introduction

There is rising awareness in science and policy of the potential scarcity of land for an increasing number of future uses. Land is mainly used for food, feed, fiber, bioenergy, and wood production as well as infrastructure. In addition, land is reserved for carbon storage, biodiversity conservation, and other ecosystem services (Eliasch, 2008; Roberts, 2008; Fischer et al., 2002; FAO, 2002; van Velthuizen, 2007; Popp et al., 2011; Lotze-Campen et al., 2010b). Natural forest ecosystems, especially tropical natural forests (Laurance, 2007) and tropical primary forests (Barlow et al., 2007), provide carbon storage (Jackson et al., 2008; Bonan, 2008; Gumpenberger et al., 2010) and maintain biodiversity (Brooks et al., 2006). Primary forests' value in sustaining biodiversity is irreplacable (Gibson et al., 2011). These valuable services are threatened by lasting deforestation (FAO, 2006) as well as human-induced degradation and fragmentation (Turner, 1996; Gullison et al., 2007). Several studies in the literature highlight the importance of forests with respect to ecosystem services. Schmitt et al. (2009) emphasize the insufficient conservation of non-fragmented natural forests in the Tropics and Subtropics within global priority areas for ecosystem conservation. Brooks et al. (2006) prioritize undisturbed natural forest ecosystems (Bryant et al., 1997; Greenpeace, 2005, p.12) to be conserved for their high biodiversity. Forest conservation programmes will only be successful if they take the economic impacts on alternative land uses explicitly into account. Grieg-Gran (2006) quantifies the costs of avoided deforestation (AD) in terms of foregone agricultural income, based on costs of alternative production systems at the country scale. At the global scale, Kindermann et al. (2008) estimate the costs of AD at different price levels for forest carbon, based on the change in forestry land values relative to agriculture. Neither of the two studies focusses on particular forest types. Mittermeier et al. (2003) provide rough estimates of the costs of conserving partly forested wilderness for biodiversity purposes.

Apart from the forest type to be conserved, the spatial design and prioritization of conservation programmes have to be defined. Grieg-Gran (2006) circumvents the issue by reducing historical deforestation rates at aggregated country scale, while Kindermann et al. (2008) build on spatially explicit changes in land values to generate spatial patterns of AD. There are basically two alternative goals to be pursued. First, forest conservation programmes could be designed to maximize the provision of ecosystem services (e.g. maximize stored carbon). Alternatively, the impact of forest conservation programmes on alternative land uses could be minimized (e.g. minimize foregone income in agriculture). To our knowledge, no study has yet compared these two options based on a comprehensive bio-economic modelling approach.

In the current study, we apply a spatially explicit global land use model to address the following research questions: What are the economic impacts of target-oriented natural forest conservation strategies on agricultural production in Sub-Saharan Africa, Latin America and Pacific Asia? What are the benefits of target-oriented natural forest conservation strategies in terms of AD and avoided net carbon emissions from land use change?

A consistent, spatially explicit land use budgeting approach helps to better initialize different land pools and track land use changes due to agricultural expansion and forest conservation.

Opponents of large-scale forest conservation for the provision of ecosystem services argue that enforcement without involvement of local stakeholders would be questionable (Hayes and Ostrom, 2005; Schwartzman et al., 2000). In this paper we assume that decision making of local stakeholders is solely determined by the economic rationale of optimizing their net benefits from using the land. This approach allows us to quantify the implicit costs of forest conservation through foregone benefits from other landuse activities, the so called 'opportunity costs'.

The next section introduces the model, the land allocation mechanism and underlying assumptions. The conceptual embedding and calculation of implicit costs (i.e. 'opportunity costs') of undisturbed natural forest conservation as well as the forest conservation scenarios are briefly described. Section 'Results' provides model output under different forest conservation scenarios followed by the sections 'Discussion' and 'Conclusions'.

3.3 Material and methods

3.3.1 Model of Agricultural Production and its Impact on the Environment

The Model of Agricultural Production and its Impact on the Environment MAgPIE (Lotze-Campen et al., 2008; Popp et al., 2010; Schmitz, 2012) is a spatially explicit recursive-dynamic global land use optimization model which minimizes the total costs of agricultural production in decadal time steps until 2055. It covers the most important agricultural crop and livestock production types in 10 economic regions worldwide to meet commodity demand. Spatially explicit bio-physical constraints and regional economic conditions are taken into account. Obtainable crop yields and carbon contents of forests are provided by the global dynamic vegetation model LPJmL at 0.5 arc degree resolution, which is equal to 50 km times 50 km at the equator (Sitch et al., 2003; Bondeau et al., 2007; Fader et al., 2010). Productive land enters commodity production as an input which is limited by the historically derived physical crop area (Fader et al., 2010) as well as additional convertible unused land. Varying crop yields based on bio-physical conditions in different locations determine the production costs per ton of output which leads to distinct patterns of agricultural land use. Input costs per hectare for labor, chemicals and other capital are calculated from the GTAP database (Narayanan and Walmsley, 2008). Rotational constraints define maximum shares of crop types per grid cell which are related to average crop rotations and agricultural management. Depending on the spatially explicit distance of cropland to major urban centers, intra-regional transport costs per ton of agricultural output are added to agricultural production costs. Transport cost estimates are derived from GTAP total transport costs (Narayanan and Walmsley, 2008), total transport time needed due to distance to major urban centers (Nelson, 2008), and total production quantity. International trade is constrained by regional minimum self-sufficiency rates. This means that a certain level of consumption has to be fulfilled within the region. The rest can be produced in other world regions according to comparative cost advantages (Lotze-Campen et al., 2008).

Cropland expansion into convertible unused land is regarded as one option to align agricultural production with projected total food consumption. It is associated with additional costs for infrastructure, land clearing, and site preparation. These costs are calculated from the access costs of forest land in equilibrium provided by the GTM database (Sohngen et al., 2009). As a second option for increasing production, the model can invest in agricultural Research and Development (RD) for technological change, in order to increase crop yields. The costs of technological change are a function of the regional technology level and have been derived from data on public expenditure on agricultural RD (Dietrich, 2011; Dietrich et al., 2013). Input costs per hectare also increase with the intensification of agricultural land use (Dietrich, 2011; Popp et al., 2011). As a consequence, shifts in land use patterns are determined by weighing marginal costs of land conversion, transport and factor inputs against marginal costs of intensification and the associated increase in transport and factor inputs.

For the purpose of this analysis, the model has been further developed. First, spatially explicit datasets for the initialization of available land pools for cropland expansion have been compiled. The available land pool has been split into 'undisturbed natural forest', i.e. the union of large intact forest landscapes (Greenpeace, 2005) and frontier forests (Bryant et al., 1997) in forestry and unused land categories (Erb et al., 2007), and 'other available land', i.e. abandoned cropland plus other natural vegetation not delineated as forest or grazing land (see Subsection 2.2.2). Datasets are harmonized at a resolution of 0.5 arc degree.

Second, the land allocation mechanism has been expanded by including additional land pools, rules, and cost types for cropland expansion and forest conservation activities. In our analysis we focus on cropland. Urban land and grazing land are kept constant in area. If land in the cropland pool gets scarce, additional land can be made available for cropland expansion from the two additional land pools, undisturbed natural forest and other available land (Appendix C, Table 2). Abandoned cropland enters the other available land pool as succession leads to natural re-vegetation. Undisturbed natural forest conservation activities do not directly compete for land. They are normatively set by international conservation policies in different scenarios. Subsection 2.4.1 provides a mathematical description of model changes.

3.3.2 Economic impact on agriculture due to forest conservation

Several calculations have been made in a post-processing procedure after model outputs had been generated. Undisturbed natural forest conservation activities restrict the location and magnitude of available unused land for crop production. Therefore, undisturbed natural forest conservation activities change the costs of production. The analysis of economic impacts from undisturbed natural forest conservation is based on the concept of opportunity costs. Generally, opportunity costs of an actual activity are defined as the foregone net benefits from not conducting the next best activity (Von Wieser, 1928). In our context, opportunity costs of a certain land-use activity are the foregone net returns per hectare of the next-best alternative type of land use. If the actual land use activity pertains to the conservation of undisturbed natural forest, the opportunity costs per hectare indicate the implicit economic value of undisturbed natural forest and the related ecosystem services, e.g. stored carbon. Based on this concept, the costs of establishing a global undisturbed natural forest conservation programme for the provision of ecosystem services to global society can be calculated as the foregone net returns from alternative land use activities. The agriculture sector may thus be compensated for providing avoided net carbon emissions or conserved biodiversity from foregone land use change. Opportunity cost estimates may serve as an indicator for the magnitude of compensation payments to make global society better off but agricultural producers not worse off.

In MAgPIE, opportunity costs can be calculated for different undisturbed natural forest conservation programmes because different spatial and temporal scales may show different impacts on agriculture.

The area of AD p^{adarea} in scenarios $sc_n \in SC$ is result of shifts in patterns of land use along the land productivity gradient taking expected transport costs of produced commodities into account. It is calculated as the difference in Business As Usual (BAU) deforestation area of undisturbed natural forest p^{darea}_{t,j,sc_1} to the conservation scenario-based deforestation area p^{darea}_{t,j,sc_n} : $sc_n \neq sc_1$, summed over the time period of forest conservation programmes with $t = s^{fcost}$ denoting the start year and T the final year of simulation. The world regions and spatial units are denoted by $i \in I$ and $j \in J$ respectively.

$$p^{adarea}_{sc_n} = \sum_{t=s^{fcost}}^{T} \sum_i \sum_j \left(p^{darea}_{t,j,sc_1} - p^{darea}_{t,j,sc_n} \right) \tag{3.1}$$

with

$$p^{darea}_{t,j,sc_n} = p^{avl}_{t-1,j,sc_n} - p^{avl}_{t,j,sc_n} - x^{fcons}_{t,j} : p^{avl}_{t-1,j,sc_n} - p^{avl}_{t,j,sc_n} \geq 0 \tag{3.2}$$

x^{fcons} denotes the area of undisturbed natural forest allocated to forest conservation. The parameter p^{avl} represents the total area of land available for crop production and forest conservation.

Total agricultural production costs in the BAU scenario are subtracted from those which accrue in conservation scenarios for each time step. While production costs are comparable in the same time step, it is not methodologically sound to compare them directly over time. Therefore, the Present Value (PV) of total opportunity costs PV_{i,sc_n}^{oc} is calculated, which constitutes the sum of foregone future cost reductions multiplied by a discount factor. A global discount rate r of five percent is assumed to cover real capital costs. For comparing opportunity cost, if conservation programmes differ in the duration of implementation over time, the average annual flow of opportunity costs over time AN_{i,sc_n}^{oc} is important, which can be derived from the total PV.

Therefore, the present value of total agricultural opportunity costs PV^{oc} is calculated first and finally converted to an annual equivalent AN^{oc} for comparison reasons.

$$PV_{i,sc_n}^{oc} = \sum_{t=s^{fcost}}^{T} (g_{t,i,sc_n} - g_{t,i,sc_1}) \; \frac{1}{(1+r)^{t \times 10}} \tag{3.3}$$

$$AN_{i,sc_n}^{oc} = \frac{PV_{i,sc_n}^{oc} \times r}{1-(1+r)^{-50}} \tag{3.4}$$

Furthermore, we calculate the share of opportunity costs in total agricultural production costs, in order to show the relative magnitude of foregone benefits. Additionally, estimates of the total opportunity costs are linked to the AD area and associated avoided net carbon emissions that constitute benefits to global society. Such benefits depend on agricultural production strategies and are not solely dependent on conservation efforts. Therefore, they indicate the average compensation payments that would accrue to the global society.

3.3.3 Scenario analysis

In our scenario analysis we distinguish two undisturbed natural forest conservation programmes: one that aims at maximizing carbon storage as an ecosystem service, and a second one that aims at minimizing the economic impact on alternative land uses. In the first case, we put priority on the contribution of undisturbed natural forests to climate change mitigation. In the second case, we emphasize the agriculture sector perspective that aims at minimizing additional costs. The magnitude of conserved undisturbed natural forest area is comparable in the two scenarios, but carbon storage has a lower priority in the latter one.

As a point of reference, the BAU scenario allows for cropland expansion into undisturbed natural forest as well as unused other natural vegetation that is at least marginally suitable for rainfed crop production. Crop suitability is based on the GAEZ project (Fischer et al., 2002) (Appendix B, Table 1).

In the full conservation scenario FC100, all undisturbed natural forest and unused naturally vegetated land (globally 734 million hectares) is excluded from the land pool available for cropland expansion (Appendix C, Table 2). The scenario FC100 serves for contrasting purposes only since it is unlikely that 100 % undisturbed natural forest conservation will be successful. Therefore it aims at grasping an upper limit of potential opportunity costs.

In FC50-Y and FC50-C scenarios, we reduce the area of protected undisturbed natural forest to 50 %, i.e. 367 million hectares globally. The undisturbed natural forest conservation programme is implemented stepwise over time and proportionally distributed across regions. Thus, the time needed for effectively implementing the undisturbed natural forest conservation programmes is taken into account. Moreover, the heterogeneity of regional undisturbed natural

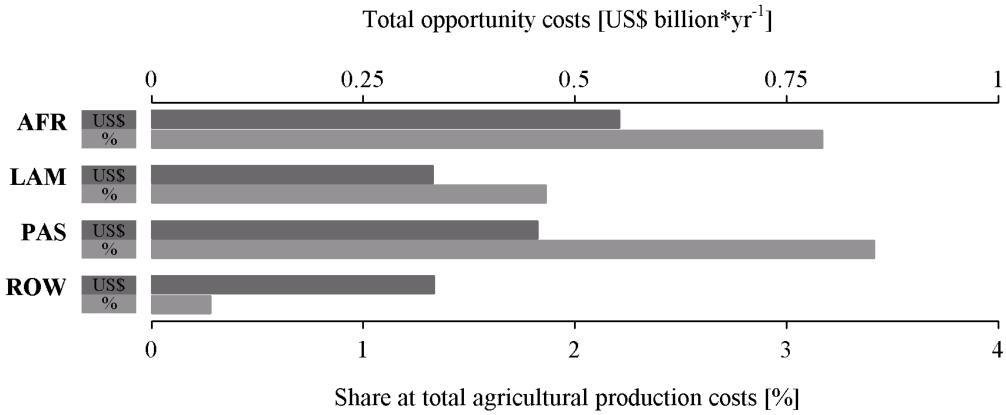

Figure 3.1: Total opportunity costs, FC100 versus BAU, 2015 to 2055

forest endowments and associated carbon density is covered. The land allocation to protected undisturbed natural forest is determined by the conservation strategy, i.e. either by minimizing agricultural opportunity costs or by maximizing carbon storage. Technically, the first strategy gives priority to the conservation of forest area with the lowest expected crop yields and thus minimizes expected opportunity costs in agriculture (scenario FC50-Y). The second strategy focuses on carbon-rich area first to maximize carbon storage of undisturbed natural forest (scenario FC50-C). Both the FC50-Y and FC50-C scenarios will differ from FC100 due to allowed cropland expansion into remaining undisturbed natural forest, which is referred to as leakage in undisturbed natural forest conservation.

The analysis focuses on three tropical regions, Sub-Saharan Africa (AFR), Latin America (LAM) and Pacific Asia (PAS). They account for 92 % of suitable undisturbed natural forests and a substantial part of total undisturbed natural forest area (43 %) (Bryant et al., 1997; Greenpeace, 2005) and have shown the highest rates of deforestation (FAO, 2006). The complementary Rest of World (ROW) is the aggregate of seven world regions in MAgPIE: Centrally-Planned Asia, Europe, Former Soviet Union, Middle East and North Africa, North America, Pacific OECD, and South Asia. The country-to-region mapping is shown in Dietrich (2011, Suppl. materials).

3.4 Results

3.4.1 Total opportunity costs of undisturbed natural forest conservation

The first set of results deals with the total opportunity costs of undisturbed natural forest conservation. Figure 3.1 shows both the absolute value of opportunity costs and their share of agricultural production costs for the full conservation scenario FC100 compared to the BAU scenario without any conservation policy. As explained above, these opportunity costs are the foregone net income from agricultural production as a consequence of undisturbed natural forest conservation.

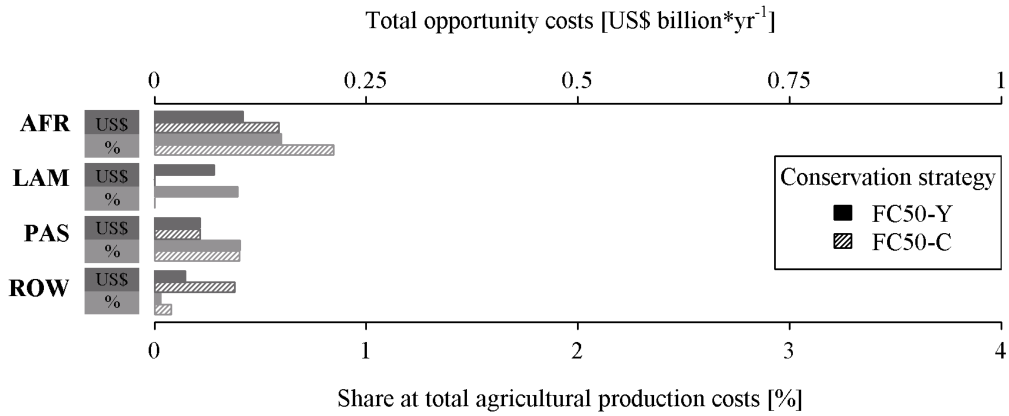

Figure 3.2: Total opportunity costs, FC50 versus BAU, 2015 to 2055

In total, three tropical regions account for more than 82 % of global opportunity costs from 2015 to 2055. Regional opportunity costs per year are between 0.3 and 0.5 billion US$, and do not exceed 4 % of agricultural production costs (PAS) in relative terms.

Disaggregated results on the composition of total opportunity costs help to understand the drivers of change (Appendix C, Table 3). Obviously, agricultural input costs for labor, capital, and chemicals are reduced, as less land is taken into production. Likewise, expenditures for preparing additional unused land for agricultural production, e.g. through land clearing and infrastructure, are saved. PAS makes an adequate example of the trend in all regions, a partial cost saving in scenario FC100 compared to BAU. Input costs, land conversion costs and, to a minor extent, transport costs are reduced in PAS by -10 %, -46 %, and -1 % respectively. On the other hand, additional investments in RD over-compensate these cost reductions, leading, in total, to positive opportunity costs in all regions (Appendix C, Table 2).

In addition to results in FC100, total opportunity costs of 50 % undisturbed natural forest conservation (FC50-Y, FC50-C) are shown in Figure 3.2.

Total opportunity costs in the minimized agricultural impacts scenario FC50-Y are plausibly smaller or equal to the maximized carbon storage scenario FC50-C, except for LAM. LAM shows zero opportunity costs in FC50-C which coincides with total transport costs that are comparable to FC50-Y, but significantly higher cropland expansion. This means that transport costs to the market per ton of output are lower in FC50-C in 2015, and more land is taken into production in the vicinity of markets. For AFR, the opportunity cost differences between FC50-Y and FC50-C are related to significantly lower average agricultural yields and carbon saved per hectare at similar magnitude of conserved undisturbed natural forest area in 2015 (e.g. 473 tons CO_2 per hectare for FC50-Y versus 605 tons CO_2 per hectare for FC50-C).

There are at least three striking results in FC50 scenarios that deviate from FC100. First, despite undisturbed natural forest conservation areas being cut by half compared to FC100, total opportunity cost estimates decline by more than 50 %. Second, total opportunity costs in AFR exceed the values in other regions, in both absolute and relative terms. However, they do not exceed 0.8 % of total agricultural production costs. Third, in LAM the total opportunity costs drop to zero in FC50-C.

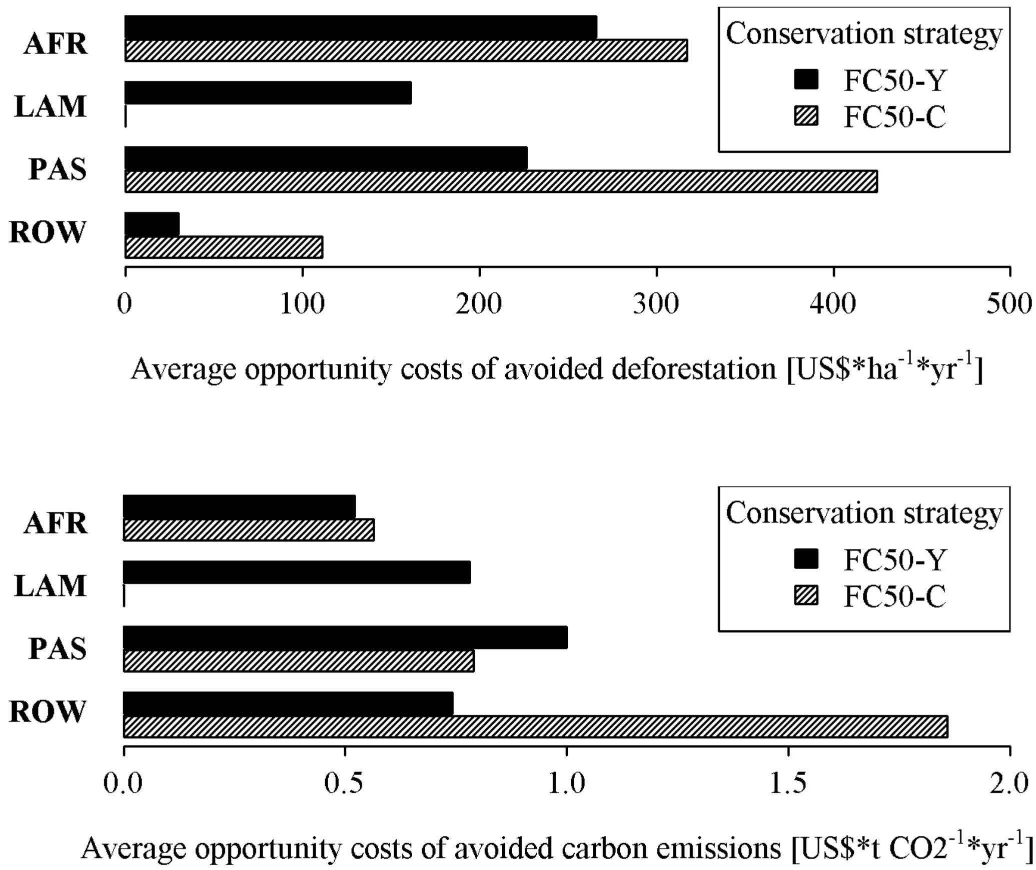

Figure 3.3: Average annual opportunity costs, FC50 versus BAU, 2015 to 2055

The economic impacts of undisturbed natural forest conservation on the agriculture sector are linked to quantifiable benefits to global society. AD and avoided net carbon emissions are ascribed to agricultural activities and these benefits exist in all regions. In Figure 3.3, upper Panel, we present the average opportunity costs per hectare of AD for the minimized agricultural impacts scenario FC50-Y and for the maximized carbon storage scenario FC50-C. The opportunity costs per ton of avoided carbon emissions for the two scenarios are displayed in Figure 3.3, lower Panel.

The average annual opportunity costs of the minimized agricultural impacts scenario (FC50-Y) and the maximized carbon storage (FC50-C) scenario are similar, except for PAS where costs per hectare are almost twice as high in FC50-C compared to FC50-Y. Furthermore, results for FC50-C in LAM and PAS differ, due to similar AD areas and avoided net carbon emissions, but relatively higher total opportunity costs in PAS.

For the full conservation scenario FC100 (Appendix C, Figure 5) average annual opportunity costs of AD are at same levels in AFR and LAM (370 US$ per hectare) but they are significantly higher in PAS (520 US$ per hectare). Regarding avoided net carbon emissions, average annual opportunity costs per ton CO2 remain only slightly lower in AFR than in LAM. This is related to a similar relationship between avoided net carbon emissions and total opportunity cost in the two scenarios.

3.4.2 Benefits in terms of avoided deforestation and avoided emissions

In our second set of results, we quantify the benefits in terms of AD and avoided carbon emissions under the three different conservation scenarios.

In the FC100 (full conservation) scenario the area of AD in AFR (1.5 million hectares per year from 2015 to 2055) is 36 % higher than in LAM (1.1 million hectares per year, Appendix C, Figure 6, upper Panel), although AFR has merely 22 % of the undisturbed natural forest area of LAM (Appendix C, Table 2). While there is displacement of deforestation activity (leakage) into undisturbed natural forest by definition in FC100, leakage into other available land does not exceed 0.1 million hectares per year in LAM and PAS compared to BAU (Appendix C, Table 4). The ratio of avoided net carbon emissions (Figure 6, lower Panel) divided by AD area indicates higher average carbon density per hectare in AFR than in LAM (150 tons per hectare versus 130 tons per hectare).

Figure 3.4, upper Panel, shows the amount of forest area actually conserved annually for the FC50-Y (minimized agricultural impacts) and the FC50-C (maximized carbon storage) scenarios. The total amount of avoided carbon emissions per year for the two scenarios is shown in Figure 3.4, lower Panel.

In LAM and PAS, the amount of AD is significantly higher for the minimized agricultural impacts scenario FC50-Y compared to FC50-C while avoided emissions are similar for both scenarios. In AFR, the maximized carbon storage scenario FC50-C does better in avoiding both deforestation and emissions.

Moreover, FC50-Y and FC50-C scenarios show a significant discrepancy between area change rates in available and conserved undisturbed natural forest (Appendix C, Table 4). The average annual area of undisturbed natural forest converted to cropland peaks at 1.1 million hectares per year between 2015 and 2055 in AFR. Similar to total opportunity costs, the AD area drops more than proportionally compared to FC100 (Appendix C, Table 4), as do changes in agricultural yields (Appendix C, Table 5).

3.5 Discussion

In a first set of results, we have analyzed the economic impacts of undisturbed natural forest conservation on agricultural crop production in tropical regions. The economic impacts are measured by the opportunity costs, i.e. the foregone net returns in agriculture due to undisturbed natural forest conservation and, hence, restricted cropland expansion. Total opportunity costs turn out to be relatively low for all scenarios and all regions. The ratio of opportunity costs relative to total agricultural production costs is low, because input costs for labor, chemicals, or capital account for a high share of total agricultural costs, but they remain insensitive to undisturbed natural forest conservation strategies. This is caused by two contrary processes. First, less cropland area is taken into production than in the baseline scenario which reduces input costs. Second, investments in agricultural RD boost crop yields and lead to higher crop-specific input costs (Dietrich, 2011; Popp et al., 2011) which mainly explain differences in total

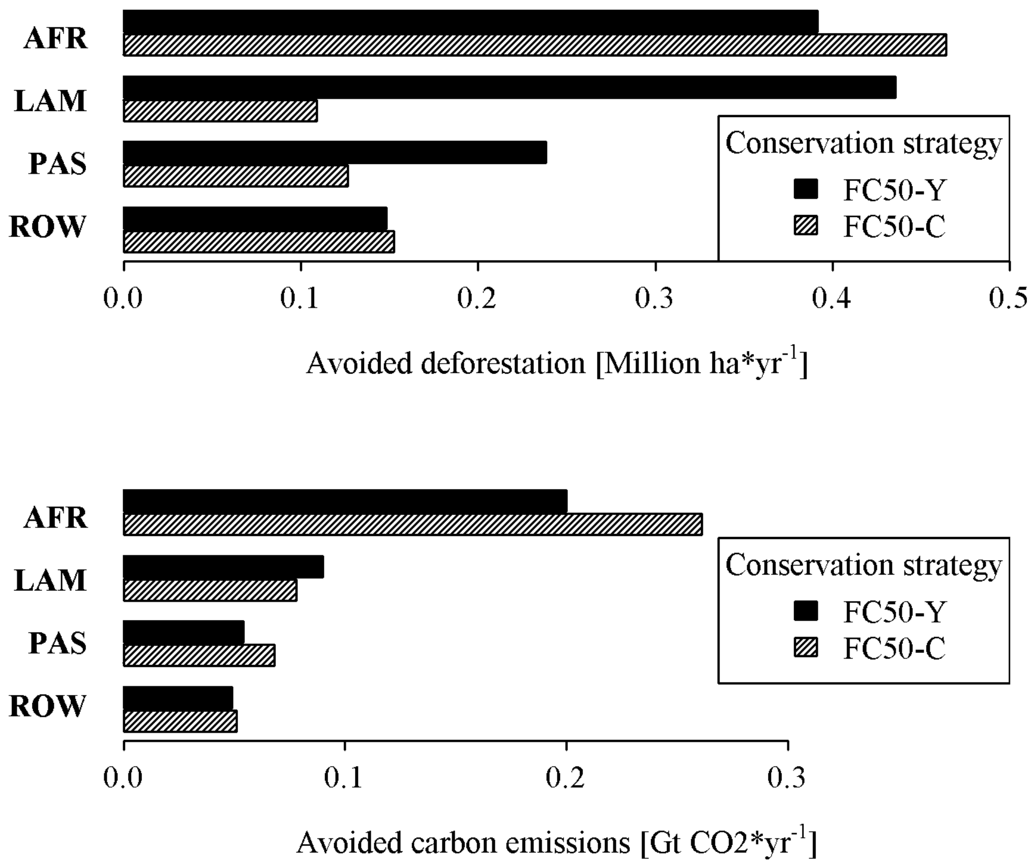

Figure 3.4: Avoided deforestation and avoided net carbon emissions, FC50 versus BAU, 2015 to 2055

opportunity costs between regions and scenarios. Apart from agricultural intensification there is also a feedback of undisturbed natural forest conservation on cropland expansion into other available land. This result is consistent with Boserup (2005) and Miles and Kapos (2008).

In Latin America, the yield based conservation allocation mechanism (FC50-Y) cannot serve as the minimizing agricultural impacts scenario because transport has a higher impact on costs than yields.

In Sub-Saharan Africa, total opportunity costs are higher than in Latin America. RD costs per unit of output grow according to a power law in our model (Dietrich et al., 2012, 2013), which mainly drives opportunity costs in Sub-Saharan Africa in connection with strong yield increases. Less suitable land for cropland expansion and the higher demand for food and feed products due to population and income growth in Sub-Saharan Africa indirectly contribute to higher total opportunity costs than in Latin America. In the past, production increases in African agriculture have been mainly achieved by cropland expansion rather than intensification (Geist and Lambin, 2006, p.74). Moreover, Sub-Saharan Africa has experienced lower rates of urbanization than Latin America and Pacific Asia (Butler and Laurance, 2008; United Nations, 2009). Nevertheless, investments in agricultural productivity increase have been low, which puts Sub-Saharan Africa at a disadvantage with respect to the economic impacts of undisturbed natural forest conservation in the future.

We have also shown results on average annual opportunity costs of undisturbed natural forest conservation. These can be used to analyze whether forest conservation will be economically attractive as a climate change mitigation option in the future. This would be the case if the average annual opportunity costs from undisturbed natural forest conservation are smaller than or equal to global carbon prices in the future. However, as there are political and technical constraints to the region-wide implementation of such conservation programmes (Ebeling and Yasue, 2008), the potential for climate change mitigation remains hypothetical.

The average costs of AD in our analysis are relatively low compared to results from Kindermann et al. (2008) for the period 2005 to 2030 (Africa: 511 US$ per hectare and year; South-East Asia: 9064 US$ per hectare and year). On the other hand, our results are significantly higher than those of Grieg-Gran (2006) for the period 2005 to 2035 (46 to 149 US$ per hectare and year for eight tropical countries). In these other studies, future technological change in agriculture is either neglected (Grieg-Gran, 2006) or implemented as an exogenous trend (Kindermann et al., 2008). Kindermann et al. (2008) calculate costs of AD based on carbon prices, but they do not take rising agricultural production costs due to intensification or leakage into other natural forest areas into account. Grieg-Gran (2006) assumes zero leakage and takes neither increasing agricultural demand nor required investment costs for agricultural RD into account. Both add to opportunity costs if agricultural land is kept constant.

In a second set of results we have addressed the benefits of undisturbed natural forest conservation, i.e. AD and avoided net carbon emissions. Benefits are obtained in all regions. If 100 % of undisturbed natural forests are conserved in Sub-Saharan Africa, Latin America and Pacific Asia, the area of AD from 2015 to 2055 in our scenario is between 30 % and 43 % of projected areas of AD in the literature (Kindermann et al., 2008). This is mainly due to the fact that we focus on the conservation of undisturbed natural forests, rather than on total forest areas. Accessibility of undisturbed natural forest is limited, compared to other available land with natural vegetation, which has also been shown by Andam et al. (2008). Loosening conservation efforts to 50 % of undisturbed natural forest area leads to substantial cropland expansion into remaining undisturbed natural forest in Sub-Saharan Africa (i.e. leakage of carbon emissions).

From an economic perspective, expansion into unprotected undisturbed natural forest delivers cost advantages compared to intensification. The spatial patterns of leakage are determined, by heterogeneous yield distribution across crop types and grid cells, distance-depending transport costs, and scarcity of available land in non-forest areas.

Large parts of previously intact primary forest in the Congo Basin have already been deforested or are threatened by deforestation (Bryant et al., 1997; Greenpeace, 2005; Wilkie et al., 2001). In the current situation, expenditures for forest conservation, e.g. in the Congo basin do not match the current opportunity costs in foregone land uses (Wilkie et al., 2001). Thus, the adequate funding for forest conservation strongly depends on the global society's willingness to pay for local conservation efforts. Without compensation payments and local stakeholder involvement the uncertainty in successful forest conservation efforts even rises (Hayes and Ostrom, 2005; Schwartzman et al., 2000). Moreover, Ebeling and Yasue (2008) stress the governance challenge for the successful implementation of AD programmes in tropical countries. Even with hypothetical adequate conservation funding, the conservation of undisturbed natural forest will put additional pressure on other ecosystem types, such as savannahs or wetlands (Miles and Kapos, 2008) which may result in rising carbon emissions. Nevertheless, the comparative analysis and prioritization of non-forest ecosystem types for conservation in an optimization framework would add substantial complexity and is beyond the scope of this paper.

Agricultural expansion due to improved accessibility of forests may trigger further economic development which raises the cost of conserving the remaining forest. On top, policies to promote bioenergy crops such as sugar cane in Brazil (Koplow and Track, 2006) substantially add to average opportunity costs of forest conservation. So, if derived demand for land in other sectors is taken into account, opportunity costs will rise significantly. Historical drivers of deforestation include not only agricultural land expansion, but also commercial logging, mining or bush meet hunting (Bryant et al., 1997; Wilkie et al., 2001). These arguments are not covered in this article and leave room for improvement in the presented modelling approach. Important aspects, like enforcement of conservation status, administration costs, timber revenues from cleared forest, additional demand for forest land from other sectors as well as a refinement of land expansion costs are left for future research.

3.6 Conclusions

We have presented an expanded version of the global land use model MAgPIE, in order to analyze the economic impacts of forest conservation strategies on agriculture. The approach presented here has several advantages compared to other studies. The focus of our analysis is on undisturbed natural forests, it covers relocation of deforestation into other natural forest areas, and it allows for endogenous technological change in agricultural production.

The synthesis of strong baseline deforestation, projected leakage, and the historical deforestation trend leads us to the following general conclusion. Deforestation continues, (1) if undisturbed natural forests are not considered for conservation programmes at all, (2) if payments to stakeholders based on opportunity costs are insufficient to serve as an incentive for AD, or (3) if other factors such as the monitoring of leakage are not taken into account.

In particular, undisturbed natural forest conservation in Sub-Saharan Africa requires substantial investments in agricultural productivity increase to meet rising food demand, while substantial relocation of deforestation still occurs. Based on the historical drivers of deforestation and factors of uncertainty not accounted for, we conclude that full implementation of a comprehensive forest conservation programme solely based on opportunity costs appears unlikely in Sub-Saharan Africa.

In Latin America, a forest conservation strategy with a priority on maximum carbon storage results in zero opportunity costs. Here, a win-win situation could be created, where carbon emission reductions may be obtained with very low compensation payments to agriculture. Relatively small annual opportunity costs in all regions lead to the conclusion that, even if agricultural RD expenditures are taken into account, undisturbed natural forest conservation is a low-cost option to reduce emissions and maintain other ecosystem services.

4 The economic potential of market-based climate change mitigation in forests and impacts on agriculture and forestry

Authors: Michael Krause, Hermann Lotze-Campen, Alexander Popp

4.1 Abstract

Recent studies have analyzed the economic potential of avoided deforestation or afforestation / reforestation activities for climate change mitigation from either the forestry or the agriculture perspective explicitly. The regional forest carbon supply from combined mitigation activities, the sectoral opportunity costs, the shifts in patterns of land use and the technological change rates have not been explicated sufficiently. The study addresses the shortage of global land use studies and covers the two land use sectors at similar level of detail and with full competition for land in one modelling framework.

Methodologically, a global agricultural land use model has been expanded by the forestry sector and detailed forest land pools. The analysis comprises the regional forest carbon supply, the cumulated economic potential of forest-based mitigation activities and the sectoral annual opportunity costs for the period 2010 to 2100. Scenarios imitate market-based climate change mitigation programmes which comprehend avoided deforestation, afforestation / reforestation or a combination thereof at varying forest carbon price levels across time.

The results show that climate change mitigation is achieved by avoiding deforestation at a carbon price of 27 US$ per ton CO_2 which eliminates more than 97 % of the annual carbon emissions in tropical regions. The cumulated economic potential from 2010 to 2100 is greater for avoided deforestation than for afforestation / reforestation (233 Gt CO_2 versus 124 Gt CO_2, 110 US$ per ton CO_2), with Sub-Saharan Africa contributing the outstanding share of 45 % of 233 Gt CO_2. Combined avoided deforestation and afforestation / reforestation programmes reduce the clearing of natural forests for forest plantation establishment and crop cultivation. By this means the effect of net carbon emission leakage into managed forests, which is triggered by avoided deforestation of natural forests, is minimized. Opportunity costs in agriculture amount to less than 10 % but make up the major share of total opportunity costs. Sub-Saharan Africa faces a 0.8 %-point change in required yield increase per year which drives opportunity cost most. The higher forest carbon prices the more attractive non-tropical regions (China, Former Soview Union) become for mitigation activities, though priority areas remain in tropical regions.

Conclusions and recommendations pertain to stand-alone afforestation / reforestation activities which indirectly exacerbate deforestation particularly in Sub-Saharan Africa. The co-benefits of avoided deforestation (e.g. biodiversity conservation) deliver strong arguments to pave the way in climate policy for global forest carbon market-based programmes that acknowledge the value added by co-benefits. Cross-sectoral mitigation activities are needed to minimize

carbon emission displacement by relocated deforestation activities. The carbon price development in conjunction with the sensitivity results suggests that future versions of MAgPIE-F need to built on more elaborated and consistent forest carbon price scenarios by using additional information to develop story lines respectively.

4.2 Introduction

Recent global and regional assessments have advanced the knowledge base on the economic potential of market-driven avoided deforestation (AD) and afforestation / reforestation (AR) activities for climate change mitigation (Metz et al., 2007). These assessments focus on two different approaches. On one hand, the economic potential of maintaining the carbon storage function of tropical forests for climate change mitigation has been analysed by establishing carbon supply curves for emission reductions from AD (Kindermann et al., 2008). On the other hand, the costs of forest carbon sequestration programmes have been analysed (Rokityanskiy et al., 2007). The production of food crops, animal feed, fibers, fuelwood and timber, together with infrastructural projects, as well as environmental considerations such as the conservation of biodiversity of ecosystems and other ecosystem services make up a backdrop of competing land use (Eliasch, 2008; Roberts, 2008; Fischer et al., 2002; FAO, 2002; van Velthuizen, 2007; Lotze-Campen et al., 2008, 2010a,b; Krause et al., 2013). The analysis of concerted carbon storage and carbon sequestration programmes with regard to other land uses may help to refine our understanding of both, the economic potential of forest carbon supply as well as of land use change implications that may possibly 'lead to unintended environmental and socioeconomic impacts that could jeopardize the overall value of carbon mitigation projects' (Canadell and Raupach, 2008, p.1457).

However, there is a shortage of global land use studies that cover the two land intensive sectors, agriculture and forestry, at a similar level of detail and with full competition for land in one modelling framework (Sathaye and Andrasko, 2007; Beach and McCarl, 2010). Moreover, global studies on the economic impacts of the combination of both, AD and AR activities on agriculture and forestry land use are scarce (Metz et al., 2007, p.558). Among the modelling frameworks currently in use, the GAINS Model framework (Boettcher et al., 2008) covers a range of greenhouse gases and deforestation, afforestation and forest management in a global forest model G4M (Benitez et al., 2007; Rokityanskiy et al., 2007; Kindermann et al., 2006, 2008) coupled to a global agriculture, forestry and bioenergy land use model GLOBIOM (Schneider et al., 2011; Havlik et al., 2011). GAINS' main applications are still restricted to regional assessment of climate policies. G4M details biophysical growth conditions and engineering costs in forests and is driven by GLOBIOM's endogenous land prices and commodity prices generated in a wider land use context.

The functionality of the recursive dynamic GLOBIOM with respect to represented land use change options is of major interest for the improved land use model development presented hereafter. GLOBIOM's land use change options allow for the conversion of pristine forest to managed forest and cropland, but do not allow for cropland and managed forest expansion to grassland or other natural vegetation (Boettcher et al., 2008). Furthermore, the wood supply is restricted to managed forests (sawnwood and woodpulp) and, by this means, is not flexible enough to allow for the wood commodity supply shift to the exploitation of unmanaged forests. In GLOBIOM, the explicit product demand functions, needed for the maximization of the producer and consumer surplus in the agriculture and forestry sectors, face the common challenge of defining the own-price elasticities of demand, which are taken from the United States Development Agency (USDA).

Another model, the GTAP model and its GAEZ extension is coupled to the GTM. Together they represent a modelling framework which combines a static CGE model with a detailed dynamic PE model for the forestry sector. Forest management intensification and land conversion to forests are modelled at GAEZ level with regard to their mitigation cost potential and thus lack the spatial explicitness of GLOBIOM and G4M integrated model (Hertel et al., 2009; Sohngen and Mendelsohn, 2007).

Mitigation options have been assessed from a stand alone forest sector perspective in a number of models; the spatially-explicit PE DIMA model, the predecessor of G4M; (Rokityanskiy et al., 2007), the regional PE Generalized Comprehensive Mitigation Assessment Process (GCOMAP) (Sathaye and Andrasko, 2007); and the PE GTM for GAEZs (Sohngen and Mendelsohn, 2003, 2007). Early estimates of the mitigation effect of a global afforestation programme make use of a bottom-up regional accounting approach on suitable and available land and growth functions (Nilsson and Schopfhauser, 1995). Rokityanskiy et al. (2007) prescribes the land required per grid cell for food production and other uses over time. Sohngen and Mendelsohn (2003, 2007) follow a similar approach.

Other studies on the global AR are restricted to the biophysical area potential closely linked to compliance climate policies under the Kyoto Protocol (Zomer et al., 2008). The regional Forest and Agricultural Sector Optimization Model (FASOM) has been applied to the US (Alig et al., 1997; Jackson and Baker, 2010) and the EU (Schneider and Schwab, 2006; Schneider et al., 2008) and extended to incorporate GHG studies (Beach and McCarl, 2010) but global applications in sectoral mitigation analysis of the model do not exist.

In the forestry chapter of IPCC's AR4, Nabuurs and Masera (2007) highlight further research need because global sectoral studies on the climate change mitigation potential through forestry give estimates that are higher than regional bottom-up studies (13.8 Gt CO_2 per year compared to 1.3 to 4.2 Gt CO_2 per year in 2030). A recent update of the contribution of deforestation to global CO_2e emissions estimates 12 % (Van der Werf et al., 2009), which is lower than the contribution estimated in IPCC's AR4 and preceeding studies (17 % per year) (Parry et al., 2007) but still significant, primarily from tropical forests (Gibbs et al., 2010).

Further studies are necessary to analyse the agriculture and forestry sector in conjunction with forest-related mitigation activities in an existing global spatially-explicit land use optimization model. The functionality needs to cover the deforestation of unmanaged forest and flexibility in wood supply from forest types. Due to challenges in the estimation of the own-price elasticity of demand for consumer and producer surplus optimization a straightforward production cost minimization approach with exogenously given commodity demand may be used for estimating the climate change mitigation potential.

The following research questions have been developed:

1. How does forest carbon supply from market-based climate change mitigation programmes in forests respond to forest carbon prices?

2. What is the economic potential of market-based climate change mitigation programmes in forests compared to other studies?

3. What are the economic impacts of market-based climate change mitigation programmes such as avoided deforestation and afforestation / reforestation on agriculture and forestry?

4. How do sectoral production patterns and required yield increase in agriculture and forestry change to meet future demand for food, feed and wood commodities?

The next section introduces the model with its sectoral extension by forestry, the refined land allocation mechanism, the concept of forest-based mitigation programmes and underlying assumptions. The scenario setup for forest-based mitigation programmes and the sensitivity analysis are briefly described and calculations presented. Section 4.4 provides model output under different conservation scenarios. Section 4.5 adds the discussion and in Section 4.6 conclusions are drawn.

4.3 Material and methods

4.3.1 Forestry in the Model of Agricultural Production and its Impact on the Environment

The Model of Agricultural Production and its Impact on the Environment (MAgPIE) (Lotze-Campen et al., 2008; Popp et al., 2010) is a spatially-explicit recursive-dynamic global land use optimization model which minimizes the total costs of agricultural production in decadal time steps until 2055. It covers the most important agricultural crop and livestock production types in 10 economic regions worldwide to meet commodity demand. Regional economic conditions and spatially-explicit bio-physical constraints are taken into account. Obtainable yields are generated by the vegetation model LPJmL (Sitch et al., 2003; Bondeau et al., 2007; Fader et al., 2010). Land enters as production input in limited supply. An available option to adapt production to match projected total food consumption is cropland expansion into available land at additional costs (Krause et al., 2013). Technological change is endogenously treated in MAgPIE, as the yield increase needed to bring supply and demand into equilibrium if resource constraints do not permit additional land use activities (Dietrich et al., 2012; Popp et al., 2011). International trade above a minimum self-sufficiency rate is facilitated by different regional technology levels in crop production, i.e. comparative cost advantages, and functions as additional means to bring supply and demand into equilibrium (Schmitz et al., 2011).

For the purpose of this study, the model has been extended. A simple representation of the forestry sector has been developed analogous to the agriculture sector with the aim to minimize global costs of wood production while satisfying a prescribed wood consumption across time.

The production of wood takes place in three forest types (Managed forest (Age-class forest), Potentially managed natural forest and Undisturbed natural forest) and distinguishes two roundwood types (Softwood and Hardwood) to produce four wood commodities (Saw logs and Veneer logs, Pulp logs, Other industrial roundwood, Woodfuel). A Leontief production function has been employed, i.e. factor inputs enter in fixed proportions with zero elasticity of substitution. In the current state, wood is treated as a homogeneous good, i.e. each commodity can be produced from each roundwood type and assortments obtainable from different dimensions and parts of the trunk and branches are neglected (see Subsection 2.1.2 and Section 2.3). In addition, carbon sequestration and carbon storage functions can be 'produced' in managed and other forest types. The commodity production in each year stems from the merchantable growing stock in forest types generated by means of the vegetation model LPJmL (Sitch et al., 2003; Bondeau et al., 2007), and the approximation of growing stock from vegetation carbon by biomass conversion and expansion functions.

Forest area is determined by available statistical data (Sohngen et al., 2009; FAO, 2006) which is integrated with spatially-explicit datasets (Ramankutty and Foley, 1999; Sitch et al., 2003) in order to refine forest land modules in MAgPIE (Section 2.2). Softwood and hardwood age-class forests are assumed to be planted, intensively managed and clearcut after an endogenously determined rotation length beyond a minimum tree age to harvest wood commodities. Natural forest is potentially managed, i.e. at least selectively cut at a sustainable harvest level with subsequent natural regeneration and protected from unsustainable harvesting. Alternatively, it is regarded as undisturbed natural forest. The latter is located too far from infrastructure, rivers, costlines to be influenced by human interventions (Krause et al., 2013; Erb et al., 2007; Potapov et al., 2008; Bryant et al., 1997).

A distinct feature of the forestry sector is the long-term commodity production (future wood supply) which is approximated by a combination of the rationally-expected derived demand for wood commodities, the future availability of natural forest as a source of income, and an uncertainty surcharge. The uncertainty surcharge is a scaling factor which adjusts the contemporary decision of planting forests to cope with the risk of wood undersupply in the future. Future undersupply may be ascribed to uncertainties in future demand and forest losses due to natural hazards. In addition, other reasons for forest establishment than wood production, such as combating desertification through additional forest land cover are implicitly covered by the scaling factor.

Decisions that involve choosing between planting forest or allocating land to agricultural production are based on a comparison of annuity costs of production. Section 2.4 provides a mathematical description of modifications in the model.

4.3.2 Economic potential and sectoral economic impacts of market-based climate change mitigation in forests

In Chapter 3 the case of a top-down command-and-control policy for climate change mitigation through forest conservation was analyzed. Market-based options may include

1. levying a carbon tax on wood harvest from natural forests (Eliasch (2008, p.90-91), Kindermann et al. (2006)),
2. subsidising AR activities for additional carbon sequestration (Plantinga and Mauldin, 2001; Kindermann et al., 2006), and
3. stimulating the demand for forest-based climate change mitigation services and creating a value of these services via a forest carbon price mechanism following the concept of Payments for Environmental Services (PES) (Wunder, 2005), were forest carbon is supplied by means of AD and AR programmes.

among others (see Subsection 1.2.1).

Levying a carbon tax on timber harvest from natural forests implies the reduction of the supplied timber quantity from natural forests which could show the economic potential of AD. The negative external effects of deforestation and carbon emissions on global society would be internalized in sectoral decision making by accounting for increased timber harvest costs. However, neither the enforcement nor the regulation of taxation is applicable in the case of illegal logging and woodfuel gathering. Furthermore, the costs of post-harvest mortality in the residual standing stock before final land clearing remain unaccounted.

This is the reason why MAgPIE-F uses the concept of PES where a transfer payment is done from the society as demander of forest carbon to the forest carbon suppliers, e.g. land users in the agriculture and forestry sectors. The positive external effects from not taking deforestation decisions in natural forests in favour of continued forest carbon sinks and storage are internalized in sectoral decision making. Without carbon valuation less climate change mitigation will be 'produced' than would be optimal for society as a whole. A competitive forest carbon market could provide monetary incentives to private and public land owners to maintain carbon storage in natural forests via AD, given that both, private and public land owners behave rationally and take appropriate measures to ensure emission reductions on the land they own. Forest carbon credits from AD contribute to the opportunity costs of deforestation as they are forfeited whenever natural forest is converted to agriculture or forestry. Therefore, the economic costs of deforestation consist of a harvest cost component and an opportunity cost component which should be considered before forestland is finally cleared for other uses. Alternatively, carbon sequestration activities through AR programmes are incentivized by forest carbon credits which periodically accrue as negative costs in cost accounting.

MAgPIE-F uses a market-based approach for climate change mitigation programmes in forests with exogenously given price development paths in a scenario analysis. The steady stream of demand for forest carbon credits is implicitly expressed by forest carbon prices. The economic potential of avoided carbon emissions from foregone deforestation and net carbon sequestration in forests, jointly referred to as forest carbon supply potential, is estimated from a vector of forest carbon prices. These prices correspond to marginal costs of forest carbon supply across regions. The mathematical description of the economic potential is given in Subsection 2.4.3.

The market-based valuation of forest carbon from (1) AD and (2) AR is conceptually integrated in the cost minimization framework in MAgPIE-F as follows. Commodity demand is exogenously given and inelastic while agricultural and forestry production strive to minimize the total costs to fulfil the demand. The term 'wood commodities' is synonymously used for 'wood raw materials' which comprise all types of roundwood including woodfuel (Figure 2.14). There is no explicit demand given for forest carbon credits, and it is assumed that the market is large enough to absorb the quantities supplied. The conceptual integration of forest carbon credits from AD is similar to that of a harvest tax, which accrues on top of the operational costs of wood harvest. Forest carbon credits are added as opportunity costs to the operational costs of forest clearing and subsequent production. This entails another important distinction to a harvest tax. The entire forest carbon stock in aboveground and belowground woody biomass pools is valued, not only the harvestable tree component.

Given the goal function G for each time step in a condensed form, let Q_{sec} denote the produced quantity in sectors (crop and livestock, and forestry), the quantity of produced wood in age-class forests in future be Q_{ffore} and the quantity of carbon sequestration from age-class forests provided in the future be Q_{fforec}. Q_{tc} shall denote the quantity of technological change tc, Q_{tp} be the quantity of transported commodities tp and Q_{vegc} be the quantity of vegetation carbon from deforestation areas (harvested area A_{hv} and cleared forest A_{lc} without wood harvest). C are the factor costs respectively while C_{cc} denotes the price per forest carbon credit. The particularity of future production in the forestry sector, Q_{ffore}, is that the corresponding costs

C_{fforec} denote annuity costs. By including periodic payments for forest carbon credits, annuity costs of future production may turn into an incentive to plant forest for carbon sequestration. The scenarios $sc \in SC$ cover AD and AR programmes.

$$\begin{aligned} \text{minimize } G = &\sum (Q_{sec}C_{sec}) + \sum (Q_{tc}C_{tc}) + \sum (A_{lc}C_{lc}) + \sum (Q_{tp}C_{tp}) \\ &+ \sum (Q_{ffore}C_{ffore}) \\ &+ \sum (Q_{vegc}(A_{hv} + A_{lc})C_{cc}) : sc_{AD} \\ &+ \sum (Q_{fforec}C_{fforec}) : sc_{AR} \end{aligned} \tag{4.1}$$

The reason for the conceptual integration of forest carbon credits from AD is twofold. First, there is no explicit forest conservation sector in MAgPIE-F that competes for land with other land use sectors based on the relative costs of production. Second, since forest carbon credits increase the opportunity cost of deforestation, forest conservation is associated with cost savings if forest carbon stocks and carbon prices are sufficiently high.

Land is allocated to either agricultural or forestry production based on the magnitude of commodity demand and relative production cost changes per hectare of allocated land. In addition, land is allocated to AD if the gross benefits outweigh the costs. The gross benefits of AD are determined by the value of forest carbon credits. The costs accrue in terms of foregone sectoral production cost reductions[1]. AD is a viable alternative to deforestation if the net benefits of AD (gross benefits minus costs) are positive. The non-harvested natural forest area is calculated by subtracting the baseline deforestation area without AD from the estimated deforestation area with AD.

The AR activities take place for the establishment of age-class forest for carbon sequestration. Forest carbon credits from AR generate income which constitutes negative costs in the cost minimization framework in MAgPIE-F. Negative costs reduce the production costs in age-class forest and lead to the establishment of a new hectare of forest once the absolute value of negative costs becomes greater than the operational costs of production. AR activities contribute to total production cost reduction, and the more productive age-class forest is, the more land is allocated to age-class forest for carbon sequestration. Reallocating one hectare of land to age-class forest for carbon sequestration triggers either unmanaged land conversion at additional costs or the land abandonment from crop and wood production which, in turn, drives sectoral production costs.

Therefore, the implementation of AD and AR programmes exerts an economic impact on the land use sectors. These economic impacts are expressed as opportunity costs, which are foregone cost reductions in agricultural and forestry production (for definition in the model, see Subsection 1.1.1 and Section 2.4). Following the same logic, negative opportunity costs denote production cost savings in a land use sector due to mitigation activities. The harvest of mature trees in stands which had been established for carbon sequestration serves as an example for such cost reductions.

[1] AD is explicitly modelled and the transaction costs of implementing AD programmes remain disregarded.

4.3.3 Carbon accounting method

Carbon removals by sink from AR, avoided carbon emissions by source from AD and forest management activities and thereby the change of the total carbon stock of the forest are calculated based on simple accounting rules. IPCC's Stock-Difference Method has been applied to the carbon accounting of deforestation (Eggleston, 2006). The carbon stock changes have been assessed as the difference between two points in time (Eggleston, 2006, p.2.12, Equ.2.8). To do so, carbon stocks in living biomass have been estimated from growing stock via biomass expansion and conversion factors, and default root shoot ratios and average carbon fractions of biomass (Eggleston, 2006). The biomass expansion and conversion factors are the quotient of 'Carbon in aboveground biomass' in forests (FAO, 2006, Tab.14) and the 'Total growing stock in forest' (FAO, 2006, Tab.11) datasets taken from the Forest Resources Assessment 2005 (Marklund and Schoene, 2006, p.21).

Forest carbon credits induce increasing total carbon stocks of age-class forest via additional AR activities compared to a baseline AR activity. If age-class forest for carbon sequestration reaches the age to produce merchantable roundwood the substitution of roundwood from natural forest is allowed to take place by higher total wood harvests coming from age-class forest compared to the baseline. The accounting of carbon removals by sink from AR activities bases on the net age-class forest area change times the associated carbon stock changes between two scenarios. However, the gross carbon removal by sink is calculated from AR, not offset by the emissions from previous cropland abandonment. This is a simplification, but the first version of MAgPIE-F assumes constant soil carbon stocks, a reason why this fact does not lead to a significant flaw of results.

The accounting of carbon emissions from deforestation of natural forest produces net emissions between the baseline and forest carbon market scenario and gross estimates between two years excluding the subsequent carbon removals by sink in age-class forest. By this means, double counting of the mitigation effect is avoided.

The accounting also comprises net carbon removals by sink from intensified management of existing age-class forest compared to a forest management reference level set by the projected baseline[2]. The improved management activities comprise target tree oriented regulation of stand density and stand value-increasing pruning and the like and are expressed as an optimum management bundle for increasing the merchantable growing stock (Subsubsection 2.3.2). The recurrent costs of production and growing stock are linearly scaled (Chapter 2). Natural forest remaining natural forest across time is assumed to grow in equilibrium of regeneration and natural mortality and the impact of selective cuts is negligible.

4.3.4 Scenario analysis

The analysis of land use interactions and economic impacts of market-based mitigation programmes such as AD, AR, and a combination thereof is based on a set of scenarios. In conjunction with a prescribed forest carbon price path, the impact of institutional barriers to AR is analyzed against the baseline scenario (Table 4.1).

The time horizon of outputs spans from 2010 to 2100 and each scenario employs an exogenously defined set of constant forest carbon prices from 1 to 110 US$. The reference forest carbon price

[2]see UNFCCC COP17 for forest management reference levels (AWG-KP, 2011).

is initialized at the 2005 level of the current forest carbon price in regulated markets. All prices are inflation-adjusted from 2010 to 2100 and are kept constant across time and thus follow Kindermann et al. (2008). Other studies either use historical energy sector carbon prices (Sedjo et al., 2001) or generate carbon prices as the outcome of economic models (Leimbach et al., 2010). The combination of forest carbon prices and the corresponding annualized mitigation potential constitutes the quasi-supply curve of cumulated forest-based climate change mitigation from 2010 to 2100. In each year, the prescribed forest carbon price actually corresponds to the marginal costs of carbon sequestration or avoided carbon emissions. The cost heterogeneity stems from a number of sectoral production activities which are differently combined in each region, the production cost structure and mitigation costs on top of production costs.

Generally, global models do not address implementation issues such as institutional barriers (likely to vary across activities and regions) in their scenarios which would drive the mitigation potential downward to the true market potential (Metz et al., 2007). In MAgPIE-F, a barrier-to-implementation parameter defines the locally convertible land of age-class forest which is afforested for carbon sequestration. The parameter expresses obstacles to large-scale AR such as policy constraints, land tenure and rural development planning aspects at aggregated level (see Subsubsection 2.3.1).

Table 4.1: Definition of scenarios of market-based climate change mitigation programmes

Scenario		Market-based programme	Forest carbon prices (US$ per ton CO_2)	Institutional barriers
S1	[BASE]	Excluded	Excluded	Excluded
S2	[AD]	Avoided deforestation	P $\{1, 11, ...110\}$	Excluded
S3	[A/R]	Afforestation / Reforestation	P $\{1, 11, ...110\}$	Included
S4	[AD + A/R]	Avoided deforestation, Afforestation / Reforestation	P $\{1, 11, ...110\}$	Included [A/R]

The baseline scenario *S1 BASE* assumes a population development up to 9.5 billion inhabitants in line with the scenario B2 of the Special Report on Emissions Scenario (SRES) while GDP per capita and its growth corresponds to SRES B1 (Arnell et al., 2004; Nakicenovic and Swart, 2000). It is assumed that contemporary concerns about non-additionality, non-permanence (AR), displacement of activities (AD) or institutional constraints (AR, AD) of forest based mitigation programmes and projects (Blujdea et al., 2010; Thomas et al., 2010; Sathaye and Andrasko, 2007; Angelsen and Wertz-Kanounnikoff, 2008) lead policy makers to not approve large-scale activities as mitigation options in regulated carbon markets. As a consequence, globally spanning forest carbon projects are dismissed from the mitigation portfolio and shifts towards other mitigation activities in other sectors take place. Eligible forest carbon projects in non-regulated markets on the global scale will not be integrated into global carbon markets.

The first alternative scenario *S2 AD* imitates the implementation of a global market-based AD programme from 2010 to 2100. Opportunity cost surcharges from foregone forest carbon credits add to natural forest clearing costs. It is assumed that institutional constraints will be overcome, i.e. global legally-binding agreements and the enforcement of climate change mitigation through the conservation of natural forest facilitate AD[3].

In the second alternative scenario *S3 A/R* forest carbon credits from a global AR programme are eligible for sale in a global forest carbon market, but AD is not valued. Institutional restrictions on age-class forest expansion such as land use and tenure policies or rural development planning are binding.

The third alternative scenario *S4 AD + A/R* integrates the activities from the two previous scenarios in a global programme. Institutional restrictions apply to the establishment of age-class forest for carbon sequestration but not to the implementation of AD.

In all scenarios, agricultural commodity trade is liberalised at a magnitude of 2.5 % per decade, 10 % in total, from 2010 to 2060 (approximately 13 % in 50 years) which is conservative compared to literature (constant trade and 10 % liberalization per decade, Schmitz (2012) based on Dollar and Kraay (2004); Conforti and Salvatici (2004)). Beyond 2060, the regional self-sufficiency rates are kept constant. Wood commodity trade is liberalized over time at the same magnitude.

4.3.5 Sensitivity analysis

A sensitivity analysis of economic outputs, namely the marginal abatement costs and the sectoral opportunity costs, has been conducted complementary to the scenarios on the integration of forest carbon markets. The aim of the sensitivity analysis of separate parameters is to indicate the need and direction of future research. However it does not substitute a comprehensive sensitivity analysis of several parameter combinations in extended parameter spaces. The sensitivity of economic outputs to changes in price development, the barrier-to-implementation parameter for AR and maximum growing stock levels has been analysed separately.

The exogenously given forest carbon price paths are assumed to develop by +2.5% and +5% per year to check the sensitivity of economic outputs due to changes in the competitiveness of forest conservation and AR activities. The constant forest carbon price deflated to the 2005 level serves as starting point.

The shift of the barrier-to-implementation parameter for AR by +2.5% and +5% allows for a higher degree of agglomeration of age-class forests for climate change mitigation.

The maximum growing stock per hectare is deemed influential on outputs of land use patterns and thus has been varied by +2.5% and +5% to be consistent with other parameter changes. A higher productivity of age-class forest impacts the requirement of land for age-class forest for carbon sequestration and thus impacts land use patterns and economic results.

[3] The conservation of natural forests could be a component of globally concerted Reducing Emissions from Deforestation and forest Degradation plus (REDD+) programmes in regulated markets first taken up by the United Nations Framework Convention on Climate Change (UNFCCC) in Bali in 2007 (UNFCCC, 2008).

4.4 Results

4.4.1 Marginal costs and economic potential of market-based climate change mitigation in forests

The first set of results pertains to the marginal costs of avoided carbon emissions *S2 AD*, net carbon sequestration *S3 A/R* and a combination thereof *S4 AD + A/R* (Figures 4.1 and 4.2). Any negative value along the x-axis constitutes additional carbon emissions compared to the baseline.

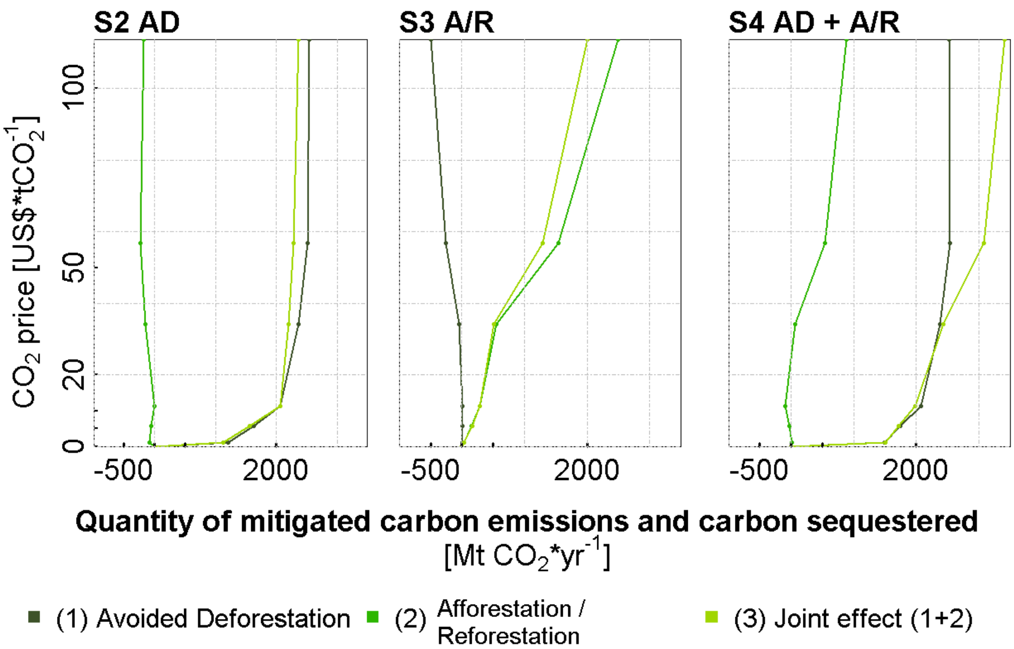

Figure 4.1: Global supply of carbon from climate change mitigation programmes

First, the very elastic part of the carbon supply curve indicates that 78 % (*S2 AD*) to 82 % (*S4 AD + A/R*) of the global mitigation potential of AD is achieved at a forest carbon price <11 US$ per ton CO_2. Beyond 11 US$ per ton CO_2, the supply of carbon for climate change mitigation becomes increasingly inelastic in all regions showing a decreasing absolute rate of additional natural forest conservation. The asymptote of mitigated CO_2 emission quantity spans from 1.2 Gt CO_2 per year in Sub-Saharan Africa to 0.3 Gt CO_2 per year in Pacific Asia and globally sums to 2.6 Gt CO_2 per year at 110 US$ per ton CO_2 (*S4 AD + A/R*).

Second, at significantly higher forest carbon prices (33 US$ per ton CO_2), climate change mitigation is complemented by AR for carbon sequestration primarily in Latin America (*S4 AD + A/R*) which is linked to the forest growth dynamics over time. The forest carbon supply (avoided emissions and sequestration) at 110 US$ per ton CO_2 per year is greatest, if market-based AD and AR programmes are implemented and fully integrated (*S4 AD + A/R*). This key result is linked to the minimized displacement of carbon emissions (leakage) if AD and AR are implemented together.

Third, Latin America is characterized by a higher climate change mitigation potential from AR at 110 US$ per ton CO_2 per year than Sub-Saharan Africa (0.6 Gt CO_2 per year versus 0.2

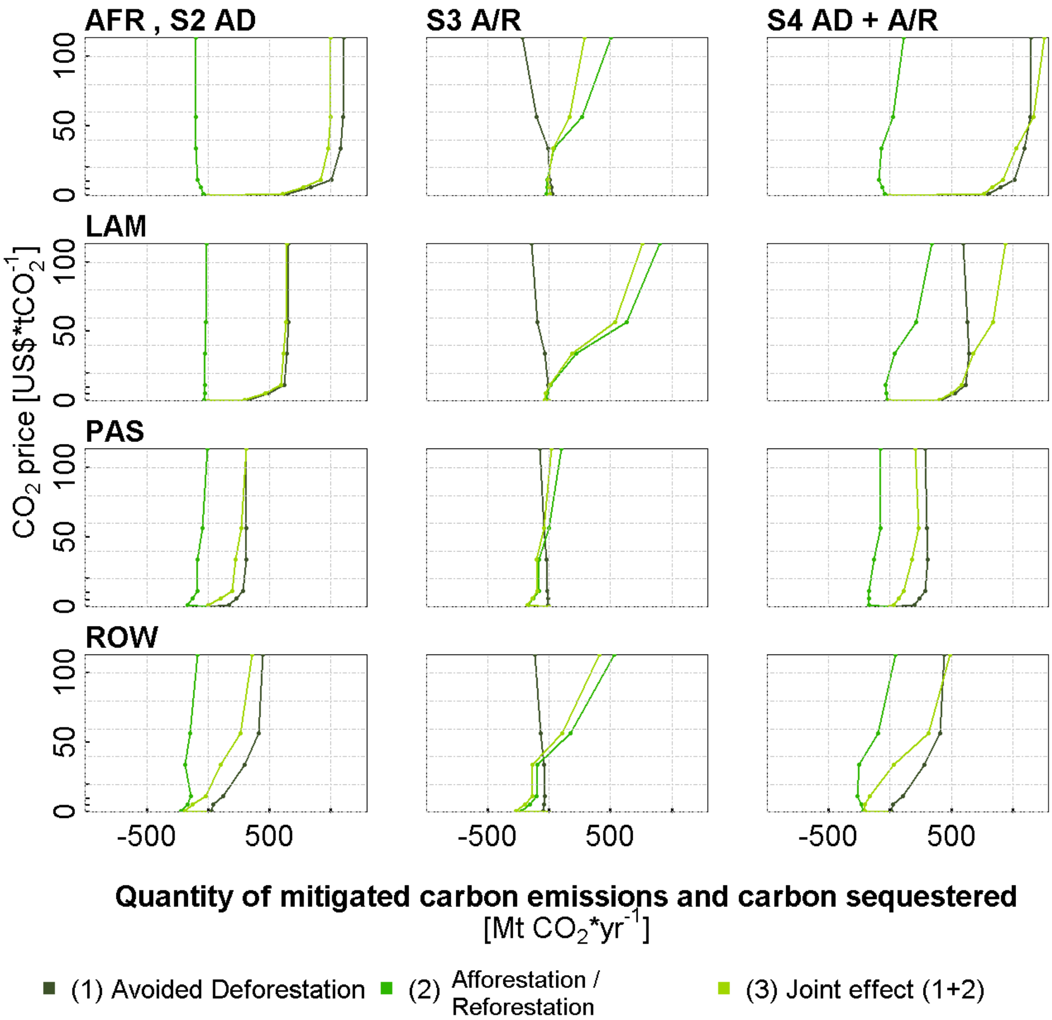

Figure 4.2: Regional supply of carbon from climate change mitigation programmes

Gt CO_2 per year) (*S4 AD + A/R*) which is to be understood in conjunction with the larger productive area available than in Sub-Saharan Africa. In contrast, Sub-Saharan Africa possesses comparative advantages in CO_2 emission mitigation from AD compared to Latin America (1.2 Gt CO_2 per year versus 0.7 Gt CO_2 per year), related to the high baseline deforestation.

Fourth, AD does not necessarily lead to a significant increase in global emissions from intensified harvest in age-class forests (*S2 AD*). In contrast, if only forest carbon from AR activities is valued, additional CO_2 emissions accrue from deforestation of natural forest (World: -0.9 Gt CO_2, Sub-Saharan Africa: -0.4 Gt CO_2 at 110 US$ per ton CO_2 per year) (*S3 A/R*).

Fifth, there is a backward bending supply of sequestered carbon (additional CO_2 emissions) in Sub-Saharan Africa up to 33 US$ per ton CO_2 per year in the integrated AD and AR scenario (*S4 AD + A/R*). Complementary to previous results, the increased wood harvest in age-class forest is related to roundwood production shifts from natural forest to implement the financially attractive AD programme.

Sixth, the marginal cost curves of AR are less elastic beyond 5 US$ per ton CO_2 compared to the scenario *S2 AD*, which expresses higher costs for the last ton of carbon sequestered compared to the last ton of avoided CO_2 emissions from AD (*S2 AD*).

As a second set of results, the economic potential of 1) avoided carbon emissions from AD, 2) carbon sequestration from AR or 3) a combination thereof is derived from supply curves and calculated as the cumulative climate change mitigation potential from 2010 to 2100.
First, the economic potential sums to 171 Gt CO_2 to 357 Gt CO_2 over 90 years at minimum / maximum if AD and AR programmes are implemented simultaneously (*S4 AD + A/R*) and prices range from 11 US$ per ton CO_2 to 110 US$ per ton CO_2. From a regional perspective, the economic potential of mitigation activities in tropical regions at 110 US$ per ton CO_2) is largest in Sub-Saharan Africa (124 Gt CO_2), followed by Latin America (117 Gt CO_2) and Pacific Asia (33 Gt CO_2).

Second, 65 % to 109 % of the total economic potential are contributed by AD (*S4 AD + A/R*, 110 US$ per ton CO_2 and *S2 AD*, 110 US$ per ton CO_2). The regional contribution to the globally mitigated emissions of 233 Gt CO_2 from AD ((*S4 AD + A/R*, 110 US$ per ton CO_2) ranges from 45 % in Sub-Saharan Africa to 12 % in Pacific Asia.

Third, the economic potential of AD is virtually unaffected by the introduction of a market for forest carbon from AR (*S4 AD + A/R*, 180 to 233 Gt CO_2). In sharp contrast, the economic potential of AR is significantly higher in the scenario of market-based AR programmes (*S3 A/R*, 3 to 234 Gt CO_2) compared to the economic potential of AR in integrated programmes (*S4 AD + A/R*, -9 to 124 Gt CO_2).

Fourth, the negative avoided emissions, i.e. additional carbon emissions from natural forest harvest (*S3 A/R*) do not drop below -81 Gt CO_2 at a forest carbon price of 110 US$ whereas 47 % accrue in Sub-Saharan Africa.

4.4.2 Economic impacts of market-based climate change mitigation in forests on agriculture and forestry

The results presented hereafter deal with the magnitude of economic impacts of forest-based climate change mitigation in agriculture and forestry. The economic impacts are expressed in terms of sectoral opportunity costs (Section 2.4 and Subsection 1.1.1) in agriculture and forestry which are ascribed to the valuation of climate change mitigation activities in forests (Figures 4.3 and 4.4).

First, the economic impacts of AD on agriculture are most prominent in Sub-Saharan Africa and the Rest of the World. Negligible economic impacts of forest carbon market programmes on agriculture and forestry in Latin America are connected to the magnitude of forest area available for land conversion.
Second, the integrated AD and AR scenario *S4 AD + A/R* shows an agricultural opportunity cost magnitude in tropical regions that sums to 88 bn US$ per year at a forest carbon price of 110 US$ per ton CO_2 for the period 2010 to 2100. This result is low compared with the economic impact of 183 bn US$ per year in agriculture in Rest of the World.

Third, the economic impact of AD in the forestry sector in tropical regions (*S2 AD*) is most pronounced in Sub-Saharan Africa on even larger scale than in agriculture (27 to 60 bn US$ per year, which translates into 45 % to 124 % higher economic impact than in agriculture).

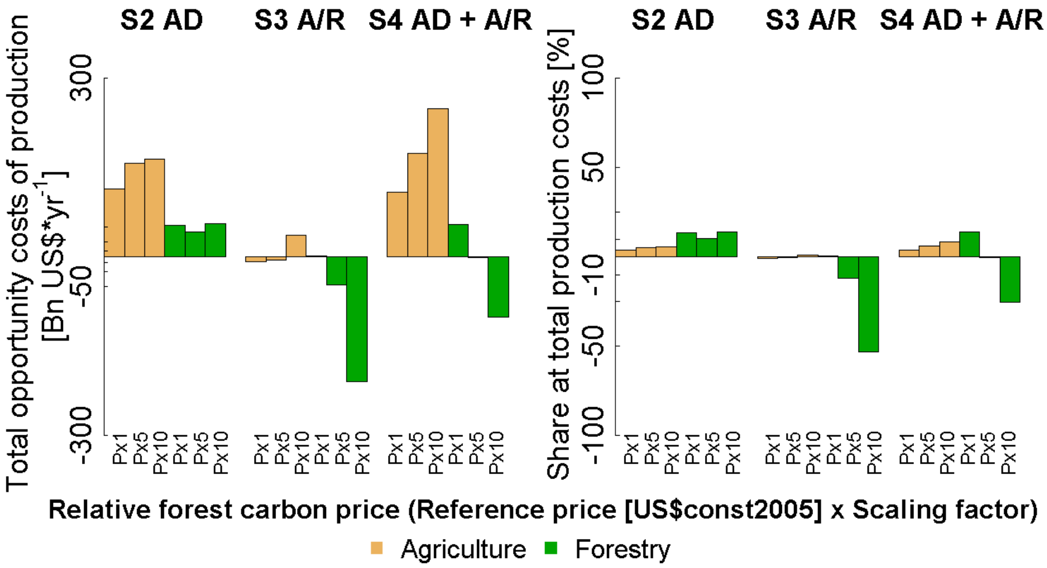

Figure 4.3: Global economic impacts of climate change mitigation in agriculture and forestry

The economic impact in the forestry sector exceeds the one in agriculture in relative terms and climbs to 49 % of the total production costs in the forestry sector at 110 US$ per ton CO_2.

Fourth, incentivizing AR activities (*S3 A/R*) results in negative opportunity costs, i.e. the higher the forest carbon price, the larger is the financial incentive to plant additional forests for carbon sequestration. The negative opportunity costs in forestry peak at -77 bn US$ (-144 % of total production costs) per year in Latin America for the period from 2010 to 2100 if the forest carbon price climbs to 110 US$ per ton CO_2. In addition, AR activities in the Rest of the World contribute -108 bn US$ (-56 % of total production costs) per year, which is equal to 73 % of the sum of tropical regions (-147 bn US$ per year).

4.4.3 Shifts in magnitude and patterns of land use with market-based climate change mitigation in forests

The fourth set of results deals with the question of shifts in the magnitude and patterns of agricultural and forestry land use due to market-based climate change mitigation programmes in forests (Figures 4.5, 4.6). The absolute annual land conversion rates are contrasted for forest carbon market scenarios versus the baseline (Appendix D, Table 9). Furthermore, the magnitude of deforestation has been compared to historical values (Appendix D, Table 10 and FAO (2010)).

First, there are managed land pools such as cropland, age-class forest and grazing land which are fully mobile across land uses. The negative value for cropland indicates a drop in cropland area expansion, while a positive value for age-class forest indicates the increase in age-class forest area expansion due to additional AR. Pertaining to available land pools covered by natural forest types, the positive value in the difference compared to the baseline stems from the reduction of the deforestation rate. In contrast, the negative difference value of the already declining land pool of other natural vegetation in the baseline indicates that the rate of conversion to managed

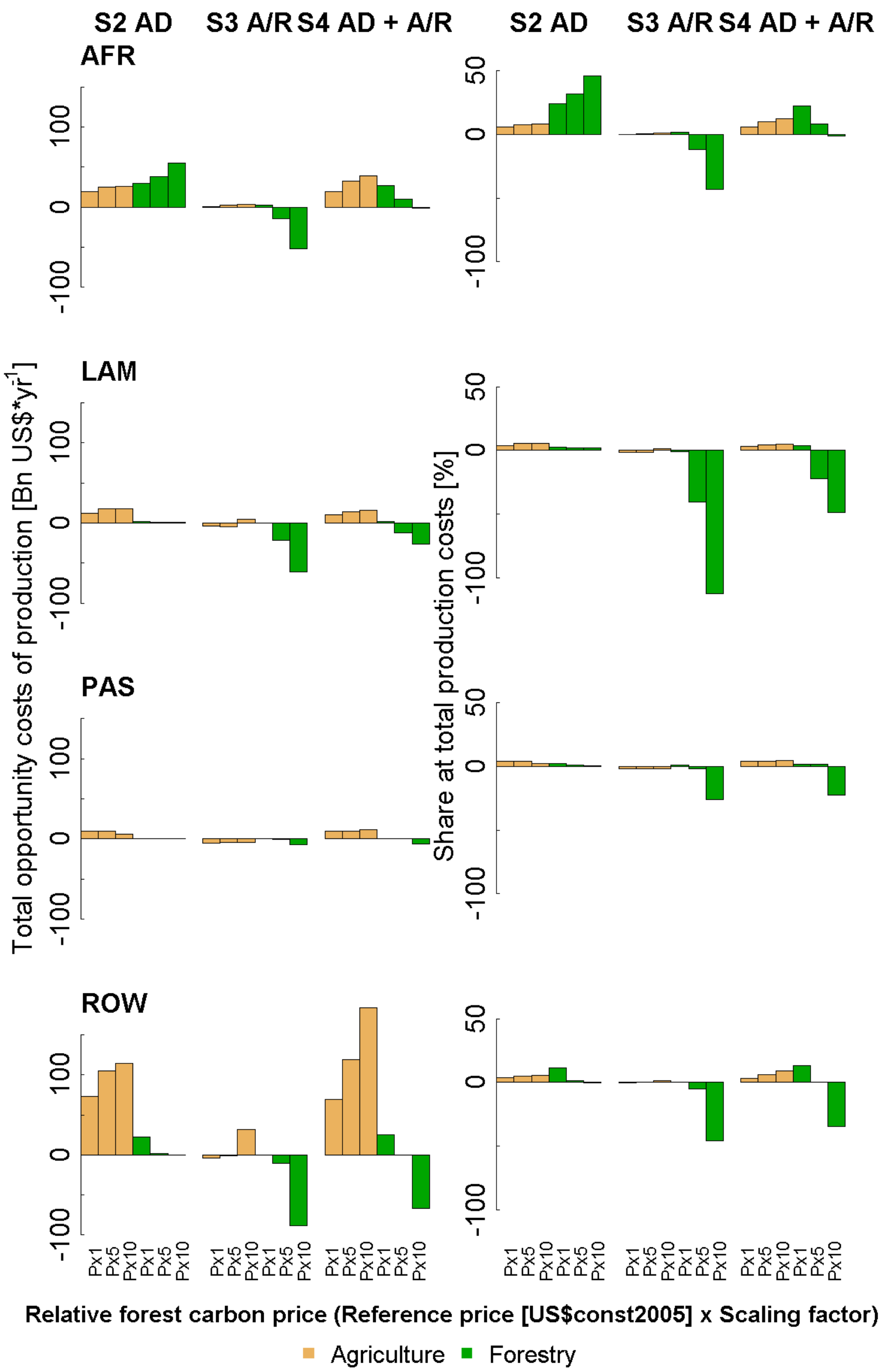

Figure 4.4: Regional economic impacts of climate change mitigation in agriculture and forestry

land is becoming greater. The list of underlying baseline land conversion rates is attached in Appendix D.

Second, the rate of AD peaks at 8.4 million hectares per year (*S4 AD + A/R*) which corre-

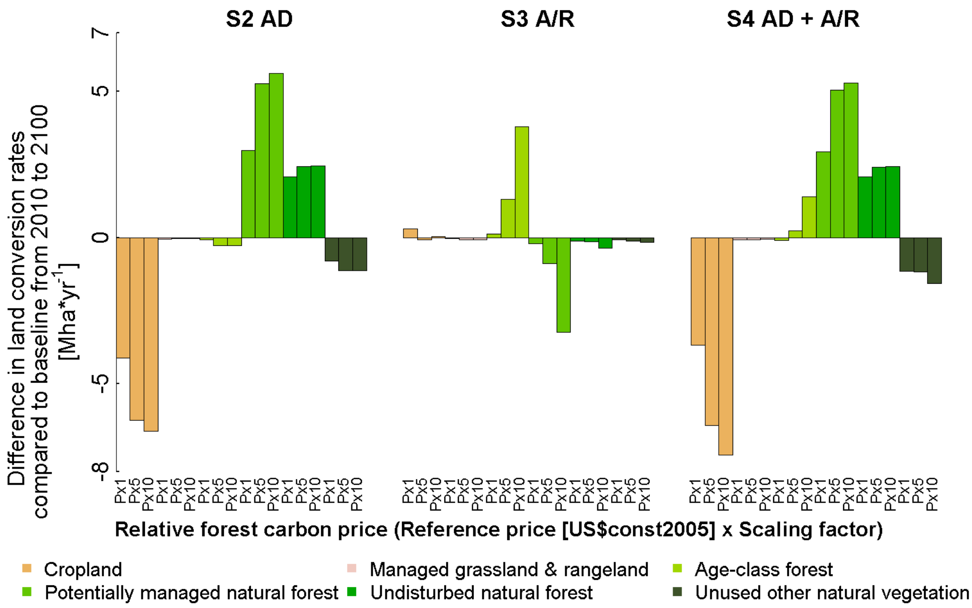

Figure 4.5: Global difference in area of land use types compared to baseline from 2010 to 2100

sponds to the reduction in deforestation of natural forests[4] by 97 % from 2010 to 2100. The age-class forest area increases by 2.1 million hectares per year compared to the baseline.

Third, in contrast to *S4 AD + A/R* the magnitude of decline in cropland expansion in *S2 AD* is smaller (-6.7 million hectares per year) than the magnitude of increase of conserved natural forest area (8.3 million hectares per year). The result is related to the foregone expansion of age-class forest (-0.3 million hectares per year) and additional conversion of unused other natural vegetation to cropland (-1.3 million hectares per year, 110 US$ per ton CO_2).

Fourth, in Sub-Saharan Africa, the foregone cropland expansion for AD peaks at -2.7 million hectares per year followed by Latin America (-2.1 million hectares per year) and Pacific Asia (-0.9 million hectares per year) (*S2 AD*, 110 US$ per ton CO_2). In all regions, the magnitude of baseline deforestation is the major determinant of the AD potential.

The shift of patterns in cropland, age-class forest, and natural forest compared to the baseline is illustrated for the year 2100 at 110 US$ per ton CO_2 (Figure 4.7).

First, the distribution of stopped cropland expansion into natural forests covers Sub-Saharan Africa (tropical evergreen forests in the Congo basin), Latin America (tropical and subtropical moist deciduous forests in Brazil and tropical forest in Bolivia), and Pacific Asia (tropical evergreen forests in Indonesia and Papua New Guinea) equally (*S2 AD*, 110 US$ per ton CO_2) (see Figure 4.7, panel 1). Additional AD is achieved in Centrally-Planned Asia (primarily subtropical and temperate deciduous forests in eastern and southern China) and in South Asia (tropical and subtropical forest types in India) which does take place at lower forest carbon prices (see Figure 4.7, panel 'ROW' and Figure 4.6, panel 'S2 AD').

Second, crop production in Sub-Saharan Africa is shifted to the southern edge of the Sahel

[4] It is the sum of 'Potentially managed natural forest' and 'Undisturbed natural forest'.

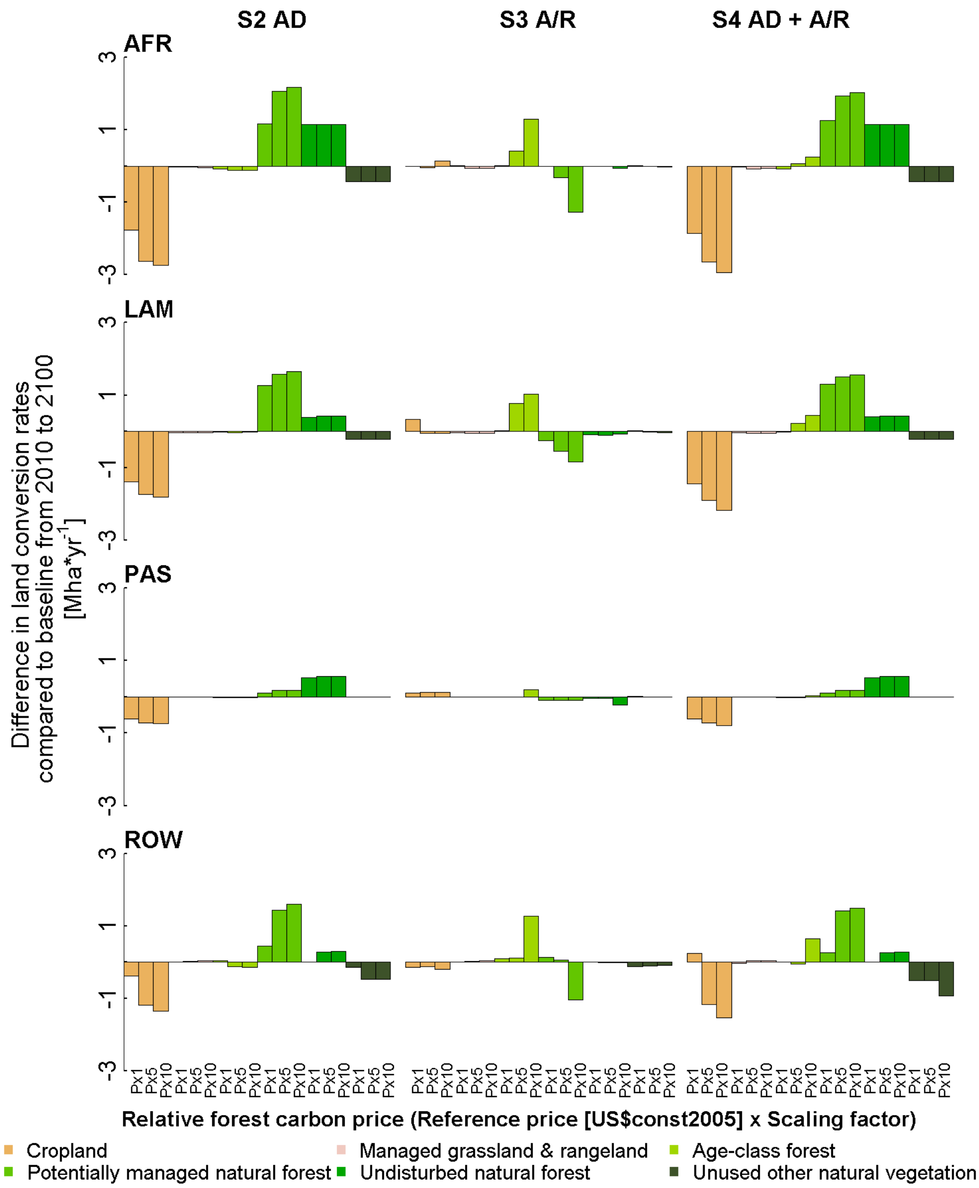

Figure 4.6: Regional difference in area of land use types compared to baseline from 2010 to 2100

zone and towards the southern tip of Africa, while in Latin America patches in the Amazon basin face additional deforestation due to leakage, i.e. the displacement of crop production from carbon-dense natural forest areas to areas with lower forest carbon density and unused other natural vegetation (*S2 AD*).

Third, a forest carbon price of 110 US$ per ton CO_2 leads to the reallocation of cropland to age-class forest, which is not only pronounced in Pacific Asia (Indonesia in particular) but also in Centrally-Planned Asia (China) (*S4 AD + A/R*).

Fourth, in the absence of AD programmes, stand-alone AR programmes lead to an equal rather than clustered spread of age-class forest establishment in all tropical regions, and productive

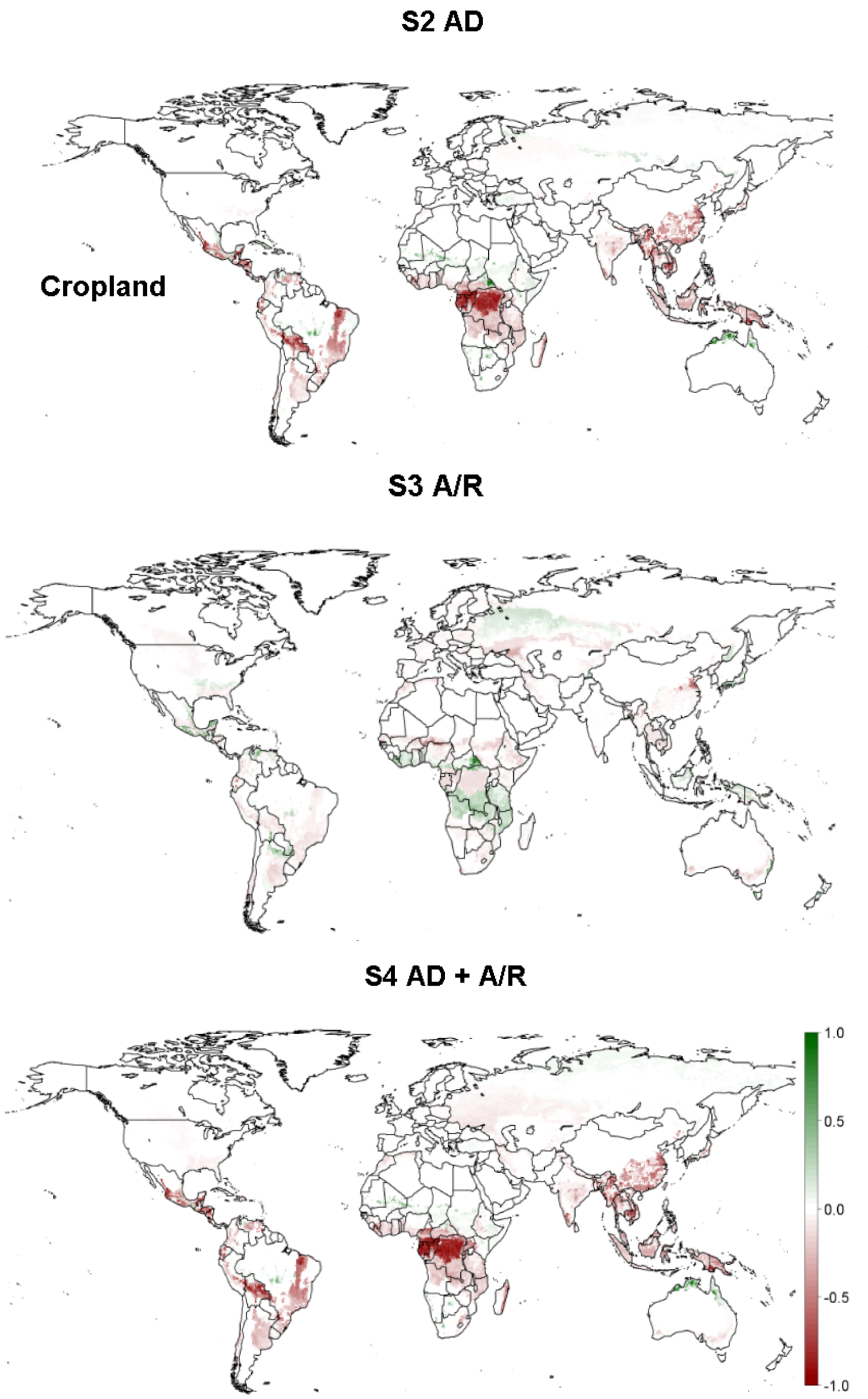

Figure 4.7: Change in cropland shares (Fraction per spatial unit) between baseline and scenarios in 2100 at 110 US$ per ton CO_2

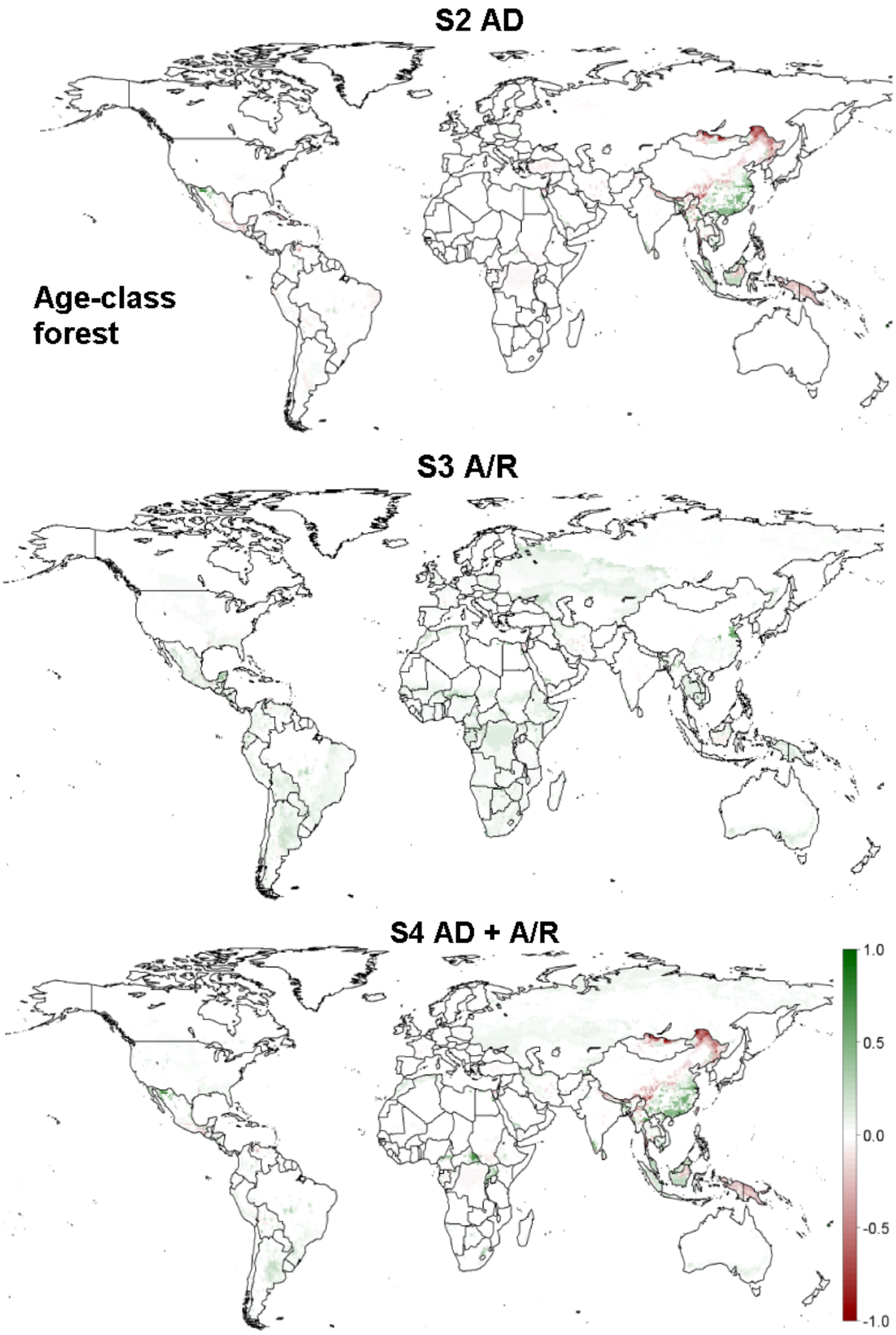

Figure 4.8: Change in age-class forest shares (Fraction per spatial unit) between baseline and scenarios in 2100 at 110 US$ per ton CO_2

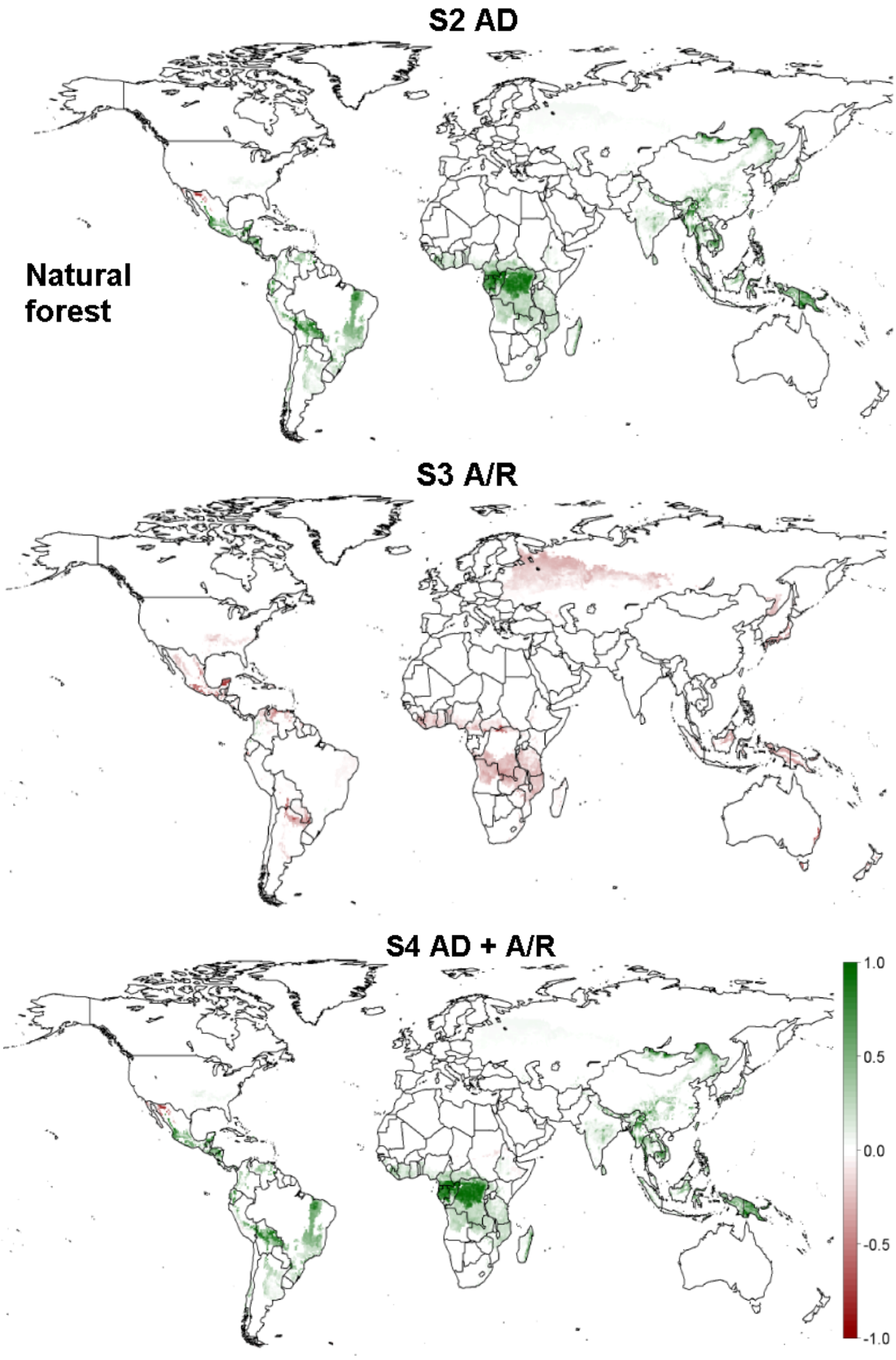

Figure 4.9: Change in natural forest shares (Fraction per spatial unit) between baseline and scenarios in 2100 at 110 US$ per ton CO_2

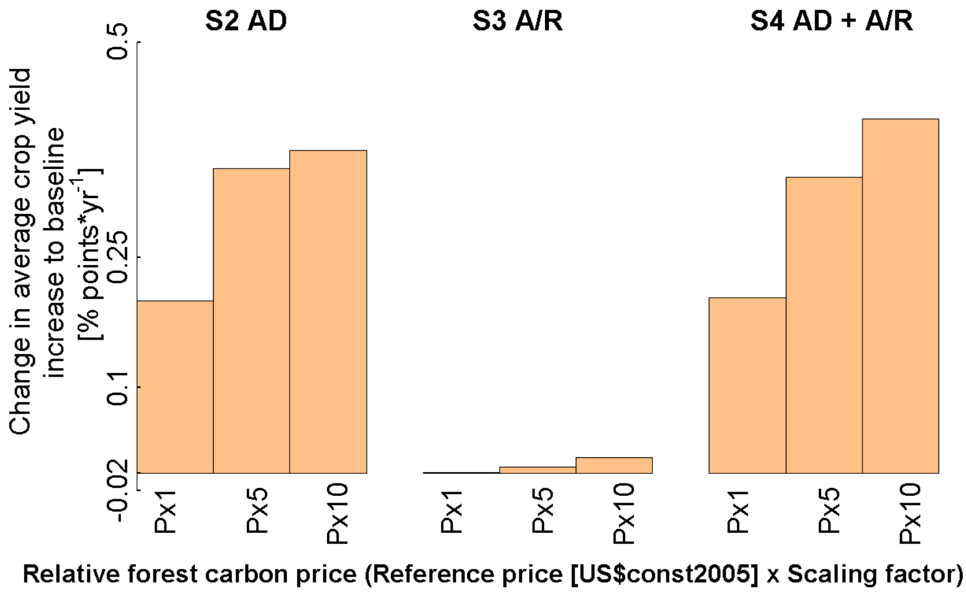

Figure 4.10: Change in average global crop yield increase compared to baseline from 2010 to 2100

parts of Central Europe and the Former Soviet Union (*S3 A/R*). The result needs to be put into perspective to the simplified implementation of the AR establishment constraints per spatial cluster.

More details on the distribution of land use types, magnitude and the time paths of regional land use changes from 2010 to 2100 are provided in Appendix D.

4.4.4 Shifts in magnitude of agricultural technological change under climate change mitigation activities

The fifth set of results points to the magnitude of the additionally required yield increase in agriculture, which becomes attractive if forest carbon valuation increases the opportunity costs of cropland expansion (Figures 4.10 and 4.11).

First, the changes in required agricultural yield increase compared to the baseline diminish with increasing forest carbon prices, explained by the non-proportional increase of technological change costs (Dietrich et al., 2013). On the global scale, the maximum difference in technological change constitutes about 0.5 %-points per year at 110 US$ per ton CO_2 in scenario *S4 AD + A/R*. However, this means that technological change has to increase by 161 % compared to the baseline increase of 70 % from 2010 to 2100 (Appendix D).

Second, negligible changes in agricultural yield increase are projected for scenario *S3 A/R* in conjunction with negligible economic impacts on agriculture but significant economic potential for carbon sequestration and impacts on forestry.

Third, Sub-Saharan Africa shows a higher baseline rate of technological change than Latin America (0.58 %-points per year compared to 0.34 %-points per year, Table 8 in Appendix D).

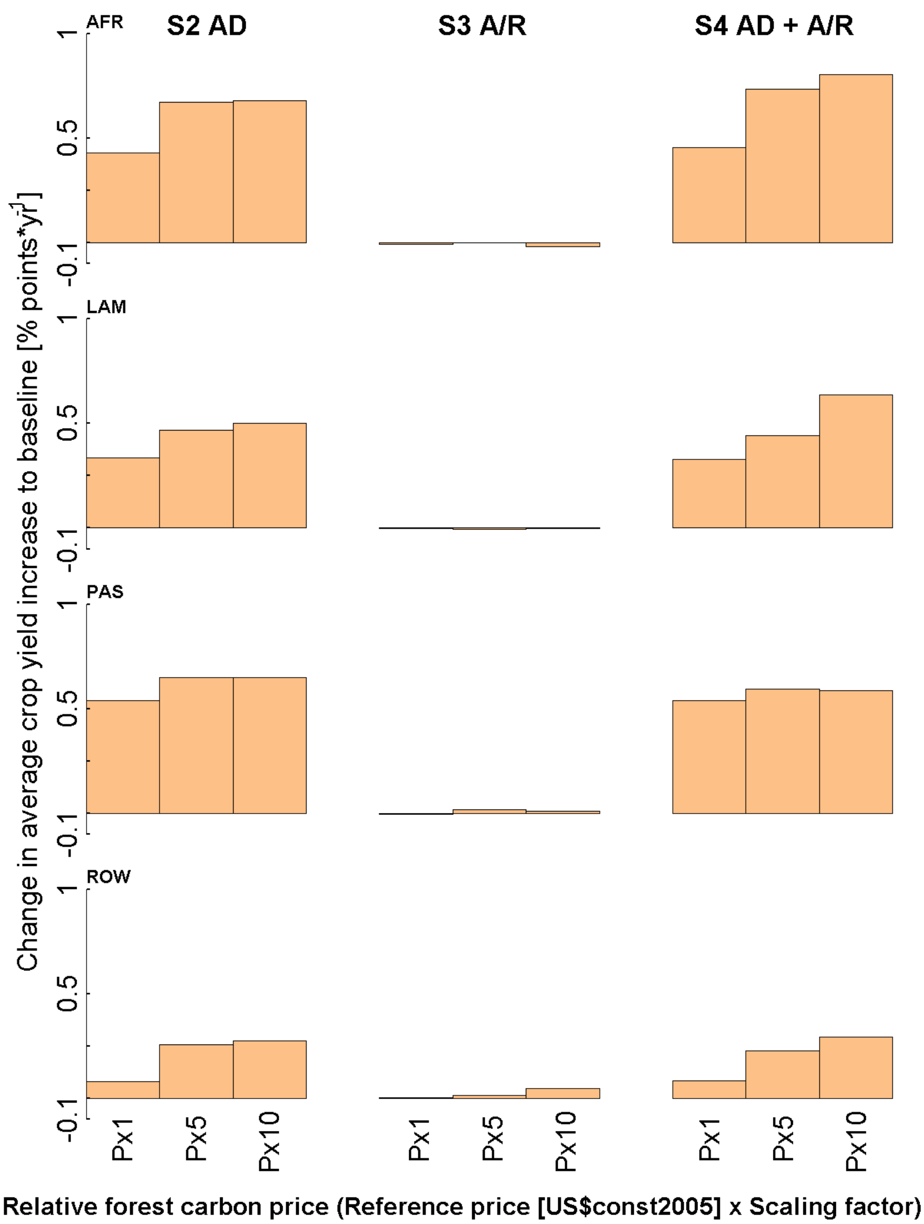

Figure 4.11: Change in average regional crop yield increase compared to baseline from 2010 to 2100

Nevertheless, the totally required technological change due to forest conservation is still highest at 0.97 %-points per year in Sub-Saharan Africa (*S4 AD + A/R*, 110 US$ per ton CO_2).

4.4.5 Sensitivity analysis

The economic potential of climate change mitigation in forests, sectoral opportunity costs, land use dynamics and technological change rates experience relative changes in case the forest carbon price paths (P), the barrier-to-implementation (B) for AR and the maximum growing stock per hectare age-class forest (G) change by 2.5 % and 5 %. The percentage changes are contrasted in Table 4.2. The Reference Δ is defined as the difference between *S4 AD + A/R* and the baseline from 2010 to 2100.

The sensitivity runs result in five major findings.

First, persistent low percentage changes of outputs indicate little influence of parameter shocks on the robustness of results. Examples are given by the change in economic potential, agricultural opportunity costs or cropland and natural forest area change in three tropical regions due to the change in the parameters on the barrier to implementation and maximum growing (Table 4.2 column 'B' and 'G').

Second, there is a more than proportional change in all output indicators to the 2.5 % (up to 105 US$ per ton CO_2 in 2100) and 5 % (up to 355 US$ per ton CO_2 in 2100) increase of forest carbon prices (table column 'P'). Third, while the increase of forest carbon price 'P' over time leads to increasing rates of technological change in all regions, the relaxation of the barrier to implementation 'B' and the maximum growing stock 'G' leads to the opposite, a slight decrease of required crop yield increase.

Fourth, a high percentage change in outputs is estimated for the economic potential, land use changes and change of required yield increase in the Rest of the World although at low absolute level regarding economic potential and yield increase.

Fifth, increasing forest carbon prices magnify the economic potential in Rest of the World in contrast to loosening the insitutional barriers to AR projects which reduces the economic potential in Rest of the World.

4.5 Discussion

4.5.1 How does forest carbon supply respond to forest carbon price changes and what is the economic potential compared to other studies?

For the first time at global level and consistent in a spatially-explicit multi-sectoral model, MAgPIE-F estimates the magnitude of forest-based climate change mitigation and forest carbon supply curves for a) AD, b) AR, and c) a combination thereof[5]. The annual carbon supply as well as the cumulative economic potential of avoided carbon emissions (AD) and carbon sequestration (AR) in tropical regions have been contrasted with the 'Rest of the World' for a time period of 90 years until 2100.

[5] At US level, the regional version of FASOM (Murray et al., 2004; Alig et al., 1997; Adams et al., 1996) has investigated mitigation strategies for global climate change in forest and agriculture sectors.

Table 4.2: Sensitivity of output to the 2.5 % and 5 % change of forest carbon prices paths (P), the barrier-to-implementation (B) for AR and the maximum growing stock per hectare age-class forest (G) compared to the reference

Model output	Economic region	Reference Value	Reference Unit	Price (P) +2.5%	Price (P) +5%	Barrier (B) +2.5%	Barrier (B) +5%	Stock (G) +2.5%	Stock (G) +5%
Economic potential	AFR	82.41	Gt CO_2	6	26	1	1	3	1
	LAM	57.26	Gt CO_2	13	82	-2	-3	-1	-1
	PAS	25.96	Gt CO_2	8	20	0	0	10	14
	ROW	4.88	Gt CO_2	625	1094	-15	-53	91	-17
	GLO	170.51	Gt CO_2	26	74	-1	-2	6	1
Opportunity costs in agriculture	AFR	17.89	Bn US$ p.a.	36	54	-1	1	0	1
	LAM	19.02	Bn US$ p.a.	30	26	-1	0	-1	-1
	PAS	14.28	Bn US$ p.a.	2	5	0	0	0	0
	ROW	80.61	Bn US$ p.a.	35	48	0	1	0	-1
	GLO	131.79	Bn US$ p.a.	31	41	0	1	-0	-0
Opportunity costs in forestry	AFR	24.62	Bn US$ p.a.	45	43	12	11	12	11
	LAM	2.44	Bn US$ p.a.	-9	-388	2	4	2	2
	PAS	0.39	Bn US$ p.a.	19	-215	5	-12	-2	-10
	ROW	22.02	Bn US$ p.a.	-80	-121	0	-7	-0	-4
	GLO	49.46	Bn US$ p.a.	-14	-53	6	2	6	4
Land use change (Cropland)	AFR	-1.74	Mha p.a.	32	74	4	4	4	-1
	LAM	-1.71	Mha p.a.	20	58	3	3	2	2
	PAS	-0.79	Mha p.a.	3	20	-4	-4	-3	-4
	ROW	-0.11	Mha p.a.	799	1268	121	65	81	100
	GLO	-4.35	Mha p.a.	42	89	5	4	5	4
Land use change (Age-class forest)	AFR	-0.10	Mha p.a.	28	-327	-11	-11	-9	-9
	LAM	0.02	Mha p.a.	444	3201	-114	-49	-125	-132
	PAS	-0.02	Mha p.a.	1	-475	1	1	2	3
	ROW	0.02	Mha p.a.	111	4036	-61	-260	49	-165
	GLO	-0.08	Mha p.a.	-99	-2423	30	71	5	67
Land use change (Natural forest)	AFR	2.32	Mha p.a.	26	43	2	2	3	-1
	LAM	1.94	Mha p.a.	14	23	4	4	3	3
	PAS	0.84	Mha p.a.	3	9	-4	-4	-3	-4
	ROW	0.26	Mha p.a.	529	564	11	6	17	11
	GLO	5.36	Mha p.a.	43	56	2	2	4	2
Technological change in agriculture	AFR	0.58	% p.a.	32	102	5	4	6	1
	LAM	0.34	% p.a.	33	153	-5	-4	-9	-4
	PAS	0.29	% p.a.	3	30	-6	-6	-5	-6
	ROW	0.07	% p.a.	280	341	17	11	20	12
	GLO	0.20	% p.a.	77	139	7	5	6	5

Sensitivity of output to shocks in key parameters (%)

Relative importance of AD in global forest carbon supply and economic potential

The direct comparison of forest carbon supply curves highlights that a high share (up to 82 %) of the mitigation potential globally is ascribed to AD at low costs (11 US$ per ton CO_2) if mitigation activities are jointly covered by forest carbon markets. Other studies estimate similar shares, see Nabuurs and Masera (2007) (GCOMAP, 66 % and GTM, 80 %) and Sathaye et al. (2005) (GCOMAP, 51 % to 78 %), which confirms the clear dominance of AD over AR in contributing to climate change mitigation at low costs[6]. In MAgPIE-F, it is cheaper to increase agricultural yields by technological change and avoid agriculture-driven deforestation than to prepare land for planting additional forest for carbon sequestration in a AR programme. In addition, the increase of agricultural production in tropical regions is associated with low per-hectare factor costs (Dietrich et al., 2013). The low opportunity costs of avoiding tropical deforestation in traditional agriculture and pasture land use are influenced by low factor inputs as confirmed by Grieg-Gran (2006). Finally, the magnitude of avoided carbon emissions in AD programmes is based on existing carbon stocks in old-growth natural forests. AD programmes are thus financially more attractive at a given carbon price than AR programmes, where carbon sequestration and thus carbon payments develop over a predefined period of time.

Sohngen and Sedjo (2006) shows that future global deforestation is brought to a halt at approximately 27 US$ per ton CO_2 from 2005 to 2055. The present study finds that approximately 30 US$ per ton CO_2 are adequate to eliminate yearly deforestation (more than 97 % of carbon emission are avoided) even though the time horizon of assessment stretches from 2010 until 2100 and MAgPIE-F's baseline CO_2 emissions from deforestation are relatively lower. The longer time horizon in MAgPIE-F implies that the baseline deforestation between 2055 and 2100 is taken into estimation of the yearly mitigation effects. They amount to 2.9 Gt CO_2 per year from 2010 to 2100 and do not match the historical CO_2 emissions of 5.9 Gt CO_2 per year in the 1990 (Watson et al., 2000). Nevertheless, this result is not implausible since deforestation rates have decreased in the decade from 2000 to 2010 (FAO, 2010). The shorter time horizon of scenarios and the intertemporal modelling approach in Sohngen and Sedjo (2006) contribute to different accumulated baseline emissions than in MAgPIE-F.

The AR mitigation potential in MAgPIE-F, 0 Gt CO_2 per year (S4 AD + A/R, 11 US$ per ton CO_2) to 2.6 Gt CO_2 per year (S3 A/R, 110 US$ per ton CO_2) from 2010 to 2100, is significantly lower compared to studies (Rokityanskiy et al., 2007). However, Nabuurs and Masera (2007) confirm that most of the global models are too optimistic on the mitigation potential of AR by neglecting transaction costs, barriers, and mitigation programme rules. As a reaction to this, Benitez et al. (2007) incorporate political and financial risk-adjusted discount rates[7] per country in land allocation to forestry which resulted in reduced carbon sequestration by 59 % at 50 US$ per ton CO_2. MAgPIE-F circumvents too optimistic estimates, first, by assumptions on the barrier rate to restrict the establishment of age-class forests for carbon sequestration per year, which is meaningful from real-world financial, administrative and governance constraints to AR projects (Thomas et al., 2010). Second, the selected discount rate gives less weight to future sequestration effects[8]. Third, the degree of conservativeness in forest growth assumptions

[6] Nevertheless the assumptions on carbon price development, employed input datasets and the modelling approach (regional versus global, sectors explicitly modelled) vary between studies and add uncertainty to results (Sathaye and Andrasko, 2007; Sohngen and Mendelsohn, 2003, 2007).

[7] Benitez et al. (2007) start at 5 % discount rate globally.

[8] MAgPIE-F uses 7 % discount rate globally, which constitutes a conservative average value.

and carbon accounting and thus magnitude of economic incentive and, fourth, the explicit competition for land of forestry and agriculture prevent an overestimation of the mitigation potential from AR. Previous arguments explain that at 11 US$ per ton CO_2 AR activities do not show a significant mitigation potential.

Concerning the mitigation potential of integrated AR and AD programmes, studies such as Fearnside (2000) acknowledge the orders of magnitude lower in carbon sequestration from plantations than from AD, which is hereby confirmed for low forest carbon prices and age-class forest. Main bio-physical reasons comprise, first, the limited area of new age-class forests for carbon sequestration. Second, in conjunction with the gradual change in forest carbon stock per hectare through net growth, the quantity of carbon uptake from the atmosphere is smaller than the carbon that is not emitted from protecting a hectare of (undisturbed) natural forest on significantly larger areas of natural forests. From an economic perspective, the value of carbon sequestration per hectare needs to cover the total costs of establishing, tending and monitoring a hectare of age-class forest, that is additional to AR for timber production.

The role of integration of market-based mitigation programmes in forest carbon emission leakage

The implementation of a forest carbon market programme that solely takes AR activities into account leads to increased deforestation of natural forest compared to the baseline. The expansion of timber production from age-class forests provides cost advantages over the conversion of natural forests where additional land clearing and infrastructure costs accrue. Nevertheless, there is an incentive in Sub-Saharan Africa, Latin America and the Rest of the World to expand age-class forest land for carbon sequestration at the expense of less productive cropland in a first time step and, in a second time step, to expand cropland at the expense of natural forest, which results in significant additional deforestation and thus emissions (scenario on stand-alone AR programme).

Natural forest conservation or reduced harvest activities in age-class forest may lead to the displacement of wood harvest and associated carbon emissions elsewhere which is referred to as leakage (Swingland, 2003). Several studies point to the threat of leakage of carbon emitting activities from additional AR for climate change mitigation (Wunder, 2008; Smith, 2002; Smith and Scherr, 2003; Schwarze et al., 2002; Alig et al., 1997)[9]. Adams et al. (1996, 1999) model the impact of AR on the deforestation of natural forests at regional but not global level[10]. In MAgPIE-F, the pricing of avoided carbon emissions from natural forest clearing leads to leakage (Figure 4.7). Increasing the harvest intensity in age-class forests replaces harvest activities in natural forests, as indicated by additional emissions from age-class forests at constant forest area (Figure 4.5 and Figure 4.6)[11]. In contrast to the leakage triggered by AD programmes in natural forests, the displacement of wood harvest activities from age-class forests to natural forests is negligible if the AR of age-class forest for carbon sequestration takes place.

[9] Leakage is mentioned even though the main criticism pertains to negative impacts of monocultural stands on biodiversity (Caparros and Jacquemont, 2003), the reduction of water runoff (Jackson et al., 2005) or unsustainability (Madlener et al., 2006).

[10] The Forest and Agricultural Sector Optimization Model (FASOM) was applied to the USA (Adams et al., 1996, 1999).

[11] Carbon stock changes in forest soils and other pools (understorey vegetation classes) from increased harvest intensity and decreased natural forest clearing will alter the net mitigation effect, which is beyond the scope of the study.

Leakage is minimized as a consequence of integrating market-based AD and AR programmes and positive climate change mitigation effects are identified in age-class and natural forests. Moreover, the high economic potential of AD is virtually unaffected by the implementation of integrated market-based AD and AR programmes. That is because leakage is not a threat to age-class forest in terms of reducing forest area but increases the harvest intensity instead. Thus, the inclusion of AR in integrated market-based AD and AR programmes does not exert significant pressure on agricultural area, which in turn allows technological change to compensate foregone production cost reductions similarly to the result from the implementation of a stand-alone AD programme.

It should be noted that apart from the level of forest carbon price and relative value of carbon in different mitigation activities, obstacles to structural adaptation of global agriculture and forestry sectors such as a) the conservative assumption on commodity trade liberalization, b) the prescribed regional self-sufficiency rates, c) the non-substitutability of inputs and outputs of production and d) institutional barriers to land conversion lead to a minimum level of leakage globally.

In order to tackle leakage comprehensively, an integrative climate policy enabling cross-sectoral mitigation programmes in the Agriculture, Forestry and Other Land Use (AFOLU) Sector is required (Eliasch (2008, p.86), Angelsen (2008) and Wunder (2008)).

The role of Sub-Saharan Africa in regional forest carbon supply and economic potential

Independent of the modelled option on market-based mitigation programmes, AD at low costs is primarily achieved in Sub-Saharan Africa followed by Latin America and Pacific Asia which is confirmed for AD by Kindermann et al. (2008) and integrated programmes by Sathaye and Andrasko (2007). The results highlight the role of Sub-Saharan Africa in natural forest conservation programmes but presuppose adequate agricultural R&D for crop yield increase, high effectiveness in implementation, good governance, and negligible transaction costs among other factors not accounted for (Krause et al., 2013).

The magnitude of carbon supply from AD in MAgPIE-F emphasizes that the average economic potential of AD in climate change mitigation is at the lower boundary in the range of top-down sectoral studies such as Kindermann et al. (2008). This is underpinned by comparing the average mitigation magnitude at 110 US$ (1.2 Gt CO_2 per year for Sub-Saharan Africa, 0.7 Gt CO_2 per year for Latin America, and 0.3 Gt CO_2 per year for Pacific Asia and 0.5 Gt CO_2 per year for the Rest of the World over 90 years) to the output of three models, the GTM, DIMA and GCOMAP (1.4 to 1.7 Gt CO_2 per year for Africa, 1.1 to 1.9 Gt CO_2 per year for Latin America, and 0.3 to 1.1 Gt CO_2 per year for Southeast Asia over 25 years)[12] (Kindermann et al., 2008).

The impact of carbon price scenarios on climate change mitigation potential across time

Sathaye and Andrasko (2007) estimate the global cumulative mitigation potential over 100 years (2000 - 2100) to exceed 3.5 Gt CO_2 per year (2.7 US$ per ton CO_2 and annual price increment of 5 %). MAgPIE-F provides cumulative mitigation estimates over a 90 years time horizon (2010

[12] The comparison of annual values is possible because Kindermann et al. (2008) also keep carbon prices constant over time.

- 2100) which are 46 % lower (1.9 Gt CO_2 per year, 11 US$ per ton CO_2) compared to Sathaye and Andrasko (2007). The explanation of the difference is threefold: First, the exponentially increasing carbon price at longer time span in Sathaye and Andrasko (2007) climbs from 218 to 355 US$ per ton CO_2 between the year 90 and 100. Already after 30 years, the carbon price in Sathaye and Andrasko (2007) matches the carbon price in MAgPIE-F which in turn remains constant. The carbon price increase in Sathaye and Andrasko (2007) provides greater incentive to invest in future mitigation options after 30 years than in MAgPIE-F, therefore the economic potential ought to exceed that in MAgPIE-F. Second, forest growing stock, growth and area data are model-specific[13] and implicate different amounts of carbon stocks and emissions avoided. Third, technological change and the land demand in the agriculture sector are not explicitly modelled in Sathaye and Andrasko (2007), which on the one hand potentially leads to overestimation of deforestation (and AD) and, on the other hand, gives too high estimates on AR area in the long run.

The AR mitigation potential in MAgPIE-F is significantly lower compared to other studies with differing carbon price development (Rokityanskiy et al., 2007). A model inter-comparison for the IPCC AR4 (Nabuurs and Masera, 2007) contrasts the GTM (Sohngen and Mendelsohn, 2003, 2007), DIMA (Rokityanskiy et al., 2007) and GCOMAP (Sathaye et al., 2005) which reproduce carbon price paths in line with Special Report on Emissions Scenarios (SRES) worlds spanning from 18 US$ per ton CO_2 to 37 US$ per ton CO_2, both at 5 % increase per year for 100 years from 2005 to 2105. The GTM results on carbon sequestration in total biomass range from 2.0 Gt CO_2 per year to 4.2 Gt CO_2 per year, GCOMAP from 2.6 Gt CO_2 per year to 3.5 Gt CO_2 per year and DIMA from 1.7 Gt CO_2 per year to 3.7 Gt CO_2 per year. The maximum economic potential of AR in MAgPIE-F neglects the incentive of shifting mitigation activities into the future expressed by the constant real forest carbon price[14].

The impact of forest carbon price paths needs to be investigated as they may significantly determine the economic potential, as Sohngen and Sedjo (2006) stress for intertemporal models. In the recursive-dynamic MAgPIE model, in which future carbon prices do not matter due to the myopic perspective of decision making, the price increase may trigger unrealistically high land use shifts and costs for technological change which have an impact on future production activities and costs.

4.5.2 What is the economic impacts of market-based climate change mitigation in forests on agriculture and forestry?

The third set of results deals with the economic impact of mitigation activities on land use sectors, i.e. the foregone production cost reductions if forest vegetation carbon is valued and taken into account. The so-called opportunity costs or implicit costs are either positive (AD) or negative (AR). Negative implicit costs accrue because production cost reductions are triggered by AR for the sole purpose of carbon credit generation. The results on the implicit costs of forest carbon conservation or sequestration programmes indicate that AD places a higher additional production cost burden on agriculture than AR does and agriculture bears the major share of total opportunity costs. If natural forest carbon remains unpriced, natural forests are cleared to

[13] MAgPIE-F uses LPJ for growth and growing stock data, statistical and remote sensing data for areas while GCOMAP uses various statistical non-spatial references.

[14] The carbon price scenarios to estimate the economic potential of AR differ and have to be compared with caution.

free land for agricultural and forestry expansion. Leaving the natural forest resources untapped, to maintain carbon storage, significantly contributes to agricultural opportunity costs as already identified for command-and-control forest conservation programmes (Chapter 3). Substantial cropland expansion into natural forest is foregone at a relatively low forest carbon price (11 US$ per ton CO_2). In contrast, the negligible foregone age-class forest land expansion into natural forest is based on negligible baseline conversion of natural forest to age-class forest.

Moreover, the higher the forest carbon prices, the more the forestry sector benefits from production cost reductions through negative costs generated from forest carbon credits for AR activities. They overcompensate additional costs of the displacement of forest harvest due to AD[15].

Sathaye et al. (2005) estimate the social welfare in the forestry sector as a change in consumer and producer surplus to increase and decrease by AR and AD respectively. In the present study, forestry production costs drop by almost 50 % per year at 110 US$ per ton CO_2, which is rather unrealistic but serves the purpose to demonstrate the functioning of the AR and negative cost mechanism in the model. In Latin America, the forestry sector is impacted most by negative production costs from forest carbon credits for AR activities which is explained by higher mean carbon densities compared to Sub-Saharan Africa (mean: 221 tons C per hectare, standard deviation: 131 tons C per hectare versus mean: 121 tons C per hectare, standard deviation 97 tons C per hectare). Although land is bound to carbon 'production' due to AR activities for a certain period of time, additional forestry cost reductions accrue from the subsequent increased availability of forest resources for roundwood production. Negative opportunity costs are also achieved by AR activities in integrated market-based mitigation programmes. From a forestry sector perspective, shifting wood commodity production from natural forest to age-class forest is not the most productive solution in the absence of forest carbon pricing. Harvesting easily accessible high yielding natural forests contributes to production cost reductions. Therefore, negative opportunity costs from an AR programme are partly counterbalanced by the induced shift of wood harvest from natural forests to age-class forests if AD and AR programmes are implemented together. The forestry sector adjusts the production share of wood commodities in age-class forests according to the rationally expected future availability of natural forest resources, and also benefits from the long-term availability of wood commodities from age-class forests for carbon sequestration. The small increase in age-class forest area relative to the almost entirely AD of natural forests indicates that the required quantity of wood can be supplied from age-class forests once mature for being harvested, and undisturbed natural forests maintain their role for the provision of ecosystem services, such as biodiversity conservation or watershed protection (Gibson et al., 2011; Potapov et al., 2008; Schmitt et al., 2009).

[15] Agriculture is projected to partly benefit from AR programmes in terms of negative opportunity costs at carbon prices smaller than 55 US$ per ton CO_2. However, this negligible effect is considered as noise in model runs, because there is no mechanism justifying it. The solver CONOPT uses a feasible path algorithm which follows a path of improving feasible points until it reaches the local optimum (Drud, 1996). Therefore, the path may not be the same between the baseline and alternative scenarios, leading to small deviations, noise, in model results.

4.5.3 How do sectoral production patterns and required yield increase in agriculture and forestry change to meet future demand for food, feed and wood commodities?

The total forest area retained or gained due to integrated market-based AD and AR programmes shows a higher range than comparable studies (Sathaye et al., 2005; Rokityanskiy et al., 2007)[16]. The comparison shows that area estimates are relatively high in MAgPIE-F. At the lower and upper boundaries of area estimates, the carbon price in literature exceeds the constant price in MAgPIE-F after 15 years and 49 years respectively in addition to 10 years' difference in the time horizon of scenarios. The AD area in MAgPIE-F turns out to be a relatively optimistic estimate which is associated with the model-specific assumptions on constraints of cropland expansion, the datasets on production cost per hectare and the carbon stocks employed.

Tightened land expansion constraints and need for technological change in tropical regions

Several options are modelled to attain low sectoral opportunity costs of AD (agriculture, forestry), AR (agriculture) or a combination of both (agriculture, forestry). Options pertain to the significant increase in investments in agricultural R&D and yield boosts, the intensification of wood harvest, the expansion of cropland or managed forest to less productive land, the changes in land use patterns or a combination thereof[17]. In integrated marked-based AD and AR programmes, technological change is relatively more important in keeping total production costs low. The opportunity costs in agriculture are primarily based on the intensification of production, which requires additional expenditures for agricultural R&D. The costs of substantial crop yield increases drive opportunity costs most in all tropical regions, but they are outstandingly high in Sub-Saharan Africa (see also Chapter 3).

Sub-Saharan Africa lacks suitable alternative land for crop cultivation if the market-based AD and AR programmes are implemented and carbon prices are high enough to make natural forest conservation and carbon sequestration competitive. The need for high investments in agricultural R&D is already uncovered in the baseline scenario of food and feed production as the highest population growth compared to other regions leads to relative scarcity of suitable land. In conjunction with the argument, that the expected increase in crop production on existing cropland is likely to slow down due to the higher risk of soil erosion (Alcamo et al., 2005), the pressure on available suitable forest land is aggravated and investment requirements tend to be higher.

Intensification also triggers increased factor costs for capital, labour and chemicals (Dietrich et al., 2013) and is complemented by changed production patterns and associated transport costs. Intensification in the forestry sector primarily refers to the shift in harvest towards younger stands (age classes) which goes along with the decrease of actual average rotation length, the decrease of average growing stocks and the increase of production factor costs per m^3 harvested wood due to diminishing productivity of machinery (law of mass per piece covering

[16] MAgPIE-F: 477 million hectares (11 US$ per ton CO_2) to 945 million hectares (110 US$ per ton CO_2 constant forest carbon prices) from 2010 to 2100 compared to Sathaye et al. (2005), Rokityanskiy et al. (2007, p.1063, Tab.2): 531 million hectares (DIMA, 5 US$ per ton CO_2 and 5 % per year) to 880 million hectares (GCOMAP, 10 US$ per ton CO_2 and 5 % per year) from 2000 to 2100

[17] Changes in commodity demand or liberalized trade are not regarded in the present model application; for further reading see Schmitz (2012); Popp et al. (2012).

felling, limbing, bunching, skidding, hauling activities) (Jirousek et al., 2007; Efthymiou, 2001; Bennett, 1996; Kellogg and Davis, 2006; Renzie, 2006).

Tromborg et al. (2000) shows the importance of technological trends in forest sector modelling. Since technological change is only implicitly included via the management bundle in MAgPIE-F, it should be explicitly addressed in future model versions.

Spatial distribution of conserved natural forest and AR in tropical regions and the rest of the world

The relatively homogeneous distribution of stopped cropland expansion into natural forests in Sub-Saharan Africa is influenced by similar costs per ton produced food, feed, fiber and fodder crops outside forests. The result is similar even if the demand for land from other uses such as bionenergy crops is considered (Popp et al., 2012), indicating the high value of stored forest carbon. The results of integrated marked-based AD and AR programmes regarding more dispersed foregone cropland expansion at Amazon forest edges in Latin America and in Pacific Asia between 2005 and 2090 are supported by Thomson et al. (2010, p.19635, Fig.2, Panel A & B). They are determined by heterogenous forest carbon densities and crop yields.

In addition, the Rest of the World is represented by China, which shows significant age-class forest establishment instead of cropland expansion in the south-eastern part of the country still at the expense of natural forest. From the global perspective, incentives for avoiding deforestation are high enough in tropical regions to induce the increase of timber supply in China which substitutes part of the supply from tropical regions to meet a prescribed global demand. However, constant self-sufficiency rates are implemented, hindering from free trade as simulated in another study (Schmitz et al., 2011).

In Sub-Saharan Africa, the stand-alone AR programme leads to an evenly distributed displacement of cropland by age-class forests predominantly in the Congo basin. These areas had been stocked by natural forest which was converted to cropland in the business as usual scenario. Cropland is established southwards and to the north of these areas at the expense of remaining natural forests, which shows that large-scale AR activities without simultaneous natural forest conservation indirectly exacerbate deforestation and are a driver of diminishing natural forest area.

The previous result is extended to all regions: Additional natural deforestation to meet given levels of commodity production per region is favoured over additional yield increase (i.e. investments in agricultural R&D) in agriculture. The benefit of decreasing agricultural production costs net of land conversion costs is higher than using timber at sustainable yield from natural forest without carbon valuation.

At the relatively high forest carbon price (110 US$ per ton CO_2) a band of productive land in the Former Soviet Union also undergoes AR at the expense of cropland, which is shifted at a similar magnitude to natural forest areas. Analyzing the impact of market-based AD and AR programmes in tropical countries only gives an incomplete picture, since the viability of forest-based climate change mitigation activities is determined by the forest value including carbon relative to the value of alternative land uses at global scale.

4.5.4 Sensitivity analysis

The sensitivity analysis underpins the importance of the forest carbon price and its development over time as a key parameter explaining uncertainties in model outputs. The finding is supported by Van't Veld and Plantinga (2005), the higher the forest carbon price increases the more sequestration is shifted to the future, which impacts the economic potential of forest carbon supply and opportunity costs in land use sectors. The forest carbon price increase by 5 % per year accelerates the expansion of age-class forest area for carbon sequestration outside tropical regions. The AR programme would not have been financially attractive otherwise in the sense that it reduces the total production costs for future wood supply. The options of wood production on expanded age-class forest area explains additional negative opportunity costs, i.e. cost savings in forestry.

The impact of the barrier to the implementation of a market-based AR programme for carbon sequestration and maximum growing stock parameters on economic outputs in agriculture is limited. The less binding the barrier to implementing AR is the more locally agglomerated is age-class forest area for carbon sequestration at the expense of other land use. The required technological change rates in the agriculture sector drop in Latin America and Pacific Asia since highly productive cropland areas are less demanded for age-class forest establishment. This result persists as long as the changes in food crop production costs rise higher relative to the changes in wood production cost savings from a market-based AR programme.
The land use dynamics in Rest of the World are very sensitive to carbon price changes across time. This result indicates that regions not explicitly discussed concerning their forest-based mitigation potential, such as China, hold an unlocked economic potential depending on the forest carbon price development. However, if institutional barriers to forest carbon project implemention are less binding, the Rest of the World faces a diminishing economic potential.

A more comprehensive sensitivity analysis is recommended to comprise input, parameter and process uncertainties pertaining to biological growth, agricultural and forestry yields, forest management such as rotation length, and intensity of thinning as well as sectoral production and transport costs.

4.6 Conclusions

MAgPIE-F covers the agriculture and forestry sector at similar level of detail and allows for analysing the economic potential of climate change mitigation and its impacts on two major land use sectors. The approach presented here has the advantage over other studies of incorporating two land-intensive sectors and both, carbon storage in natural forests and carbon sequestration through AR activities. The analysis builds on PE sectoral demand and production interactions and allows for endogenous technological change in agricultural production and land reallocation across sectors.

Based on the result compared to literature, it is concluded that from a climate perspective the economic potential of AD in contributing to climate change mitigation at low costs exceeds that of AR activities. It is further concluded that non-accounted co-benefits of AD such as biodiversity conservation provide non-marketed ecosystem services as 'added value' to society on top of the low cost economic potential, which puts strong arguments in favour of AD over AR activities.

The comparison to literature pinpoints that the magnitude of deforestation may be brought to a halt at approximately 30 US$ per ton CO_2 carbon price. However, this study takes the most relevant land use sectors explicitly into account. It is concluded that the land use model extended by the forestry sector addresses the shortage of global models treating agriculture and forestry endogenously. It is further concluded that the magnitude of mitigation potential ranges between bottom-up empirical estimates and top-down sectoral model outcomes, while the absolute marginal costs per ton CO_2 from AD are comparable and plausible.

Given the analysis of stand-alone AD or AR programmes versus integrated marked-based AD and AR programmes the conclusion is drawn that integrated AD and AR programmes need to be developed as a component of cross-sectoral mitigation activities to minimize carbon emission displacement by activity leakage. This conclusion supports the climate policy endeavours and findings by other studies of scaling up from carbon projects to programmes.

The importance of the carbon price development over time in conjunction with the sensitivity results suggest the following conclusion. Future versions of MAgPIE-F need to built on more elaborated and consistent forest carbon price scenarios by using additional information to develop story lines respectively.

The results show that agriculture bears the major share of total opportunity costs if deforestation is effectively avoided and AR activities are effectivly implemented, though at a relatively low level. Changes in land use patterns and significant investments in agricultural R&D are required. It is concluded that the global forestry sector is less impacted by opportunity costs and benefits from sufficient availability of wood resources from managed forests in the short run. Additional wood supply from AR and intensified harvest reduces opportunity costs in the long run.

For the agriculture sector it is concluded that on top of additionally required technological change which already drives global opportunity costs, non-accounted obstacles may threaten the success of forest conservation and forest carbon sequestration programmes. Particularly developing regions like Sub-Saharan Africa are unlikely to achieve a high effectiveness in forest conservation, required change in land use patterns and investments in agricultural R&D.

5 Synthesis, policy recommendations and suggestions for further research

5.1 Synthesis and policy recommendations

5.1.1 Justification and methodological contributions

The role of forests and respective policy options for climate change mitigation are widely debated in the climate and land use policy arena. Scientific studies provide arguments in favour of expanded and more effective normative forest conservation for ecosystem services and, among them, carbon storage and sequestration. Other studies pinpoint the economic potential of market-based forest conservation, management and expansion of forests from the climate change mitigation perspective. Scientific studies commonly account for the operating cost of forest-based climate change mitigation activities. The opportunity costs of land are either not included or are flawed by not incorporating multiple land use sectors at similar levels of spatial and thematic detail.

The doctoral thesis aims 'to contribute to the analysis of the economic impacts of forest-based climate change mitigation on competing land uses and the potential of global forests for climate change mitigation'.

An existing agricultural land use optimization model, MAgPIE, has been extended methodologically and by its input database in line with Objectives O7 and O8 (Subsection 1.1.2). Extensions comprise: the processing and integration of consistent spatially-explicit land pool datasets (Subsections 2.2.2 and 2.2.3) and vegetation carbon datasets of natural and age-class forest types via LPJ and spatially-explicit Chapman-Richards forest volume growth functions (Subsubsection 2.3.1), the definition and integration of the forestry sector including factor cost (Subsubsection 2.3.2), intra-regional transport cost (Subsubsection 2.3.2), land conversion costs (Subsubsection 2.3.2), mixed-effect and non-linear regression models on forest product consumption (Subsection 2.3.3), the setup of current and future demand-supply balances, resource constraints, production constraints and accounting of annualized production costs (Subsection 2.4.2). The consistent spatially-explicit land pool datasets have been used already in other applications (Dietrich et al., 2013; Popp et al., 2012, 2011; Fader et al., 2013).

The synthesis links the findings from two model applications: the benefits as well as the economic impacts of normative forest conservation programmes (Chapter 3) and market-based climate change mitigation programmes in forests (Chapter 4). Outstanding results from the two studies are linked to the corresponding objectives of the thesis.

5.1.2 Benefits of normative forest conservation and market-based climate change mitigation in forests

Climate change mitigation-related benefits from normative forest conservation (Subsection 3.4.2, Section 3.5) and market-based climate change mitigation programmes in forests (Subsection 4.4.1, Section 4.5) have been analysed, assessed and contrasted to other studies in line with Objectives O1 to O3 (Subsection 1.1.2). The two studies refer to the economic potential of AD and avoiding carbon emissions. The analysis of market-based climate change mitigation makes a step beyond and compares the economic potential with and without carbon sequestration from AR and includes forestry as additional competing land use sector.
In general, the economic potential is determined by changes in the interplay of managed land expansion, land use intensification, trade and associated costs of commodity production from pursuing climate change mitigation programmes. The economic potential of normative forest conservation strategies depends on targets to minimize impacts on agriculture and to maximize carbon storage and the magnitude of foregone cropland expansion into natural forests compared to the baseline (Subsection 3.3.3 and 3.4.2). In contrast, the forest carbon supply potential depends on hypothetical forest carbon price scenarios and the valuation of avoided carbon emissions from natural forest growing stocks and sequestered carbon from additional forest establishment and growth (Subsections 4.3.4 and 4.4.1).
The comparison of the two studies regarding the economic potentials of AD and avoided carbon emissions allows synthesizing into four findings and formulating policy recommendations:

I Importance of improving the representation of baseline agents and drivers of carbon emissions from deforestation in global land use modelling

Comparing the mitigation potentials of the first and the second study (Chapters 3 and 4) reveals the importance of defining the baseline drivers of natural forest deforestation. While the first study only covers agricultural crop cultivation, the second study includes both, agriculture and forestry. In the first study (Chapter 3), undisturbed natural forests can be cleared without the explicit modelling of forestry land uses. The projected annual baseline deforestation in undisturbed natural forests from 2015 to 2055 ('Available IFF, BAU', Appendix C, Table 4) corresponds to the historical annual deforestation in primary forests of Latin America, Sub-Saharan Africa and Pacific Asia from 1990 to 2010 (FAO, 2010) (4.0 versus 4.1 million hectares per year). The deforestation magnitude in other forest types and associated costs remain unexplained. They in turn would exert an impact on the magnitude of cleared undisturbed natural forest and potential of avoided carbon emissions, which is likely to be lower than estimated in Chapter 3, Figure 3.4.

In the second study (Chapter 4), the forestry sector implementation allows for wood harvest from natural and age-class forests and dynamic forest area changes. The pressure on natural forests is increased on top of the derived demand for additional cropland. The annual baseline deforestation rate in global forests for the time horizon from 2015 to 2055 exceeds the historical deforestation rate of global forests (FAO, 2010) by 33 % (Table 10), because food, feed and wood demand are expected to rise. However, the rate of deforestation in undisturbed natural forests is 28 % lower compared to historical deforestation rate of primary forests of 4 million hectares per year. It is considered that other forest types are accessible for managed land expansion. Andam et al. (2008) underpin the relatively low probability of deforestation of conserved forests if not conserved by being less accessible and of lower agricultural productivity than non-conserved forest.

The explicit modelling of multiple land use sectors and the coverage of forest types are considered to generate superior estimates of baseline deforestation and carbon emissions which is decisive for analysing the economic potential of AD. However, Thornton and Herrero (2010) stress that livestock, and in particular cattle ranging in Latin America plays an important role in deforestation. Thus, including the grazing sector as additional driver of deforestation in the Tropics is expected to further improve baseline estimates. The need for aggregated and standardized baselines has already been taken up by (Schwarze et al., 2002).

II High economic potential of market-based climate change mitigation programmes and complementary benefits from normative forest conservation

Given the aforesaid, the economic potential of avoided carbon emissions from normative forest conservation programmes is limited due to the baseline definition and cropland land expansion into parts of conserved forest areas. Compared to literature, modelled normative forest conservation only contributes an equivalent of up to 40 % to the economic potential of global AD (Kindermann et al., 2008) since the total area of protected forests is larger than the area threatened by deforestation. 1 US$ per ton CO_2 in market-based climate change mitigation would suffice to achieve the economic potential of normative forest conservation programmes, assuming that 50 % of undisturbed natural forests worth to be conserved are actually conserved. Given expected carbon prices in the future, the economic potential of market-based climate change mitigation exceeds that of normative forest conservation programmes. The analysis of market-based climate change mitigation in forests reveals that 90 % of the economic potential of AD can be reached at a carbon price of 30 US$ per ton CO_2. The magnitude is similar to values from the literature (Sohngen and Sedjo, 2006). Compared to AD the economic potential of AR programmes remains limited due to the low to moderate land productivity of planted areas. Productive land is mainly used for agriculture instead of age-class forest for carbon sequestration, though agricultural land displacement takes place if carbon prices are sufficiently high (Figure 4.7).

It is acknowledged that the objective of normative forest conservation programmes comprises a broader set of ecosystem services (Dudley, 2008). Notwithstanding the limited economic potential of avoided carbon emissions, effective normative natural forest conservation programmes provide other ecosystem services to society such as the maintainance of soil and water protection as well as high biodiversity (Brooks et al., 2006). Nevertheless, the modelled effective enforcement of forest conservation remains hypothetical. The effectiveness of forest conservation depends on factors not covered in this analysis, such as institutional capacity for law enforcement and enabling policies in place (Garnett et al., 2007) and sufficient budgets of protected area administration, which may not be fulfilled e.g. in the Congo Basin (Wilkie et al., 2001). Predisposing factors to deforestation such as commercial logging, mining or commercial bush meat hunting threaten large areas of intact natural forest ecosystems (Bryant et al., 1997; Wilkie et al., 2001) and have not been accounted for. Estimating the institutional potential and accounting for predisposing factors has been beyond the scope of the doctoral thesis.

III Regional economic potential of forest-based climate change mitigation jeopardized by carbon emission leakage

The economic potential of avoided carbon emissions from normative forest conservation programmes in Sub-Saharan Africa exceeds the potential in Latin America and Pacific Asia (Figure 3.4). The economic potential depends on the foregone agricultural production benefits from not clearing an additional hectare of natural forest. Additionally, it depends on the area of regional natural forests which can be allocated to forest conservation or agricultural land use respectively. Latin America's economic potential is associated with relatively low foregone production benefits which has been analysed and discussed in Section 3.5. Similar to normative forest conservation programmes, the economic potential of market-based AD programmes in Sub-Saharan Africa is larger than in Latin America (Figure 4.2) where transport distances and associated costs impact the baseline deforestation and thus the economic potential. Pacific Asia's lower economic potential is achieved at higher costs compared to other tropical regions.

An important determinant of the regional economic potential of forest-based climate change mitigation is the threat of displaced land use activities from AD or AR programmes and associated carbon emissions. The so-called leakage effect takes place within a region and between regions in MAgPIE-F and has been recognized in the real world as domestic leakage within national boundaries and international leakage (Jonsson et al., 2012). Displaced agricultural land use activities from conserving undisturbed natural forests reduces the economic potential in Sub-Saharan Africa and Latin America by causing additional deforestation and carbon emissions in unprotected forest areas (Figures 4.2 and 4.9). From an economic perspective, expanding into the remaining available intact and frontier forest still delivers agricultural cost advantages compared to intensification. The economic potential of market-based AD programmes is constrained by leakage as most clearly shown for Sub-Saharan Africa in Figure 4.7. Miles and Kapos (2008) stress the potential conversion of other natural ecosystems such as wetlands or savannahs from displaced land use activities, which have not been modelled in the study. The current state of international leakage by illegal timber trade and the global response are provided by Lawson and MacFaul (2010).

Implementing the market-based AR programme as stand-alone climate change mitigation activity poses the threat to natural forests of additional emissions from natural forest loss which counterbalances the economic potential of AR (Figures 4.1 and 4.2). This happens because the value of land in managed carbon forests is increased, leading to additional land expansion at the frontier of managed land and unused natural forest. This result coincides with the theory of land allocation (Subsection 1.2.1 and Figure 1.1) and empirical evidence from agricultural intensification (Angelsen and Kaimowitz, 2001; Yaron, 2001). The effect of the additional clearance of natural forest from afforestation for biofuel production has been investigated by Havlik et al. (2011). The negative effect of AR on increased natural forest conversion has already been discussed by Alig et al. (1997). Deforestation may also take place due to the displacement of agricultural activities from another region to a certain region because forest area expansion for climate change mitigation is incentivized in another region (Meyfroidt and Lambin, 2009). Valuing AD counterbalances the unintended effect in Latin America from incentivised AR programmes which leads to additional deforestation (Chapter 4). Policies or regulations may trigger leakage too (Schwarze et al., 2002), which adds uncertainty to results presented in Section 4.5.

IV Environmental and social threats associated with the economic potential of forest-based climate change mitigation

Social and environmental threats of forest-based climate change mitigation remain unaccounted in modelling the economic potential of AD and AR programmes. Particular managed land expansion at the expense of natural forest leads to fundamental changes in the ecosystem's characteristics and associated changes in the type and extent of ecosystem services apart from carbon storage and sequestration. The environmental threats comprise the reduced provision of other ecosystem services, such as surface water runoff regulation, the prevention of soil erosion, or reduced intact habitats for endangered plant and wild animal species (Duraiappah et al., 2005; Adeel et al., 2005; Diaz et al., 2006). The decrease in the provision of aforementioned ecosystem services constitute costs to society and factoring them in would decrease the economic potential of market-based AR programmes.

AD programmes may pose social threats in terms of conflicts with *de jure* or customary logging rights of forest users (Lawson and MacFaul, 2010) or traditional practices of shifting cultivation (Varma, 2003). Fearnside (2000) pinpoints the higher uncertainty of success in AD because interactions of agents, drivers, and underlying causes are less well understood. The United Nations Framework Convention on Climate Change (UNFCCC) requires social and environmental safeguards to protect non-carbon values of forests as a prerequisite to implement REDD+ projects and several suggestion have been provided (McDermott et al., 2012; Pistorius, 2012). Adequate compensation payments and local stakeholder involvement in benefit sharing reduce the uncertainty in successful forest conservation efforts (Hayes and Ostrom, 2005; Schwartzman et al., 2000). The forest carbon prices therefore need to be higher to attain a certain level of mitigated carbon emissions than modelled in this study to cover costs of livelihood programmes in REDD+ programme implementation. Eco-tourism development in communities at the natural forest frontiers could be an option (Ghazoul et al., 2010). Sub-Saharan Africa remains promising with regards to the mitigation potential at low costs if effective forest conservation is supplemented by REDD+ programmes and significant agricultural yield boosts are achieved.

Five policy recommendations are derived from previous findings:

1. There is need to facilitate research to better integrate baseline estimates of deforestation across spatial scales and reflect the understanding of agents and processes driving deforestation in standardized baseline projections aggregated to regional scales.

2. Strong arguments have been presented to create a better link between normative forest conservation and market-based AD programmes. Payments for carbon credits from AD programmes could serve as source to co-finance normative forest conservation, which is of importance given the insufficient budgets of protected area administration, e.g. in the Congo Basin.

3. Deforestation at the natural forest frontier stems from the displacement of agricultural crop production due to AR programmes for carbon sequestration on cropland. Therefore careful land use planning and its implementation needs to ensure that regional AR programmes are not located in the vicinity of natural forests to avoid the clearing of natural forests, neither directly nor indirectly. It is recommended to integrate AR and AD programmes and compare them to multi-sectoral baselines in order to assess the combined economic potential of climate change mitigation.

4. Domestic leakage from AD programmes need to be understood and tackled through mea-

sures which ensure local benefit sharing in combination with local livelihood options except the clearing of forest. International leakage, particularly through illegal timber trade, needs to be monitored. AD programme-induced forest clearing in other regions needs to be addressed by strict enforcement of policies to prohibit the trade of illegally-sourced timber.

5. Mechanisms are required to establish social and environmental safeguards for climate change mitigation programmes on a regional scale.

5.1.3 Economic impacts of normative forest conservation and market-based climate change mitigation in forests

The economic impacts of normative forest conservation on agriculture (Subsection 3.4.1, Section 3.5) and market-based climate change mitigation programmes on agriculture and forestry (Subsection 4.4.2, Section 4.5) have been analysed, assessed and contrasted to other studies in line with Objectives O4 to O6 (Subsection 1.1.2). The two studies deal with the opportunity costs of forest conservation and incentivised AD and AR programmes, which result in foregone production cost reductions. Changes in managed land patterns, land use intensification, trade and associated costs of commodity production are inherent major drivers of the economic impacts in land use sectors and covered by the two studies (Subsections 3.3.3 and 3.4.1, 4.3.4 and 4.4.2). The analysis of market-based climate change mitigation programmes takes a step beyond the scope of the first study. The second study (Subsection 4.3.4) compares the economic impacts with and without carbon sequestration from AR and includes forestry as additional competing land use sector.

The comparison of the two studies regarding the economic impacts allows synthesizing into two findings and formulating policy recommendations:

I Low opportunity costs of normative forest conservation but carbon price dependency in market-based climate change mitigation programmes

Normative forest conservation programmes and market-based climate change mitigation programmes in forests exert an economic impact of less than 10 % of agricultural production costs (Subsections 3.4.1 and 4.4.2). Predominant drivers are increased investments in agricultural productivity increase, additional land conversion costs and transport costs of commodities from more distant production to intra-regional market centers (Subsection 3.4). It has been shown that regional differences in Latin America, Sub-Saharan Africa, and Pacific Asia stem from different growth rates in food demand, land availability and crop productivity (Section 3.5). Particularly in Sub-Saharan Africa, high opportunity cost-driving rates of the required yield increase would have to be sustained until 2055. This is true since less area of other productive land than in Latin America could serve as substitute for potentially converted forest, and high population growth (Geist and Lambin, 2006; CIESIN et al., 2000) means higher commodity demand than in other regions (Section 3.5). In sharp contrast, Latin America benefits from a win-win situation, zero opportunity costs in agriculture while forest conservation areas are established normatively. This is due to the sufficiently available productive area and only moderate population pressure and commodity demand in future. According to the overall results, undisturbed natural forest conservation appears to be a low-cost but also low-potential option for greenhouse gas emission reduction (Subsection 5.1.2). The finding pertains to the future potential but has already been evidenced for the past (Andam et al., 2008).

The two studies do not only look at the opportunity costs of using land at the current state productivity (Grieg-Gran, 2006) but at the opportunity costs in agriculture where technological change is endogenous (Subsection 3.4 and 4.4.2). On one hand, increasing forest carbon prices result in increased opportunity costs from foregone crop and wood production cost reductions which is prominent on a regional scale in Sub-Saharan Africa and the Rest of the World. On the other hand, the higher the forest carbon prices, the more the forestry sector benefits from production cost reductions through negative costs generated from forest carbon credits for AR activities. The higher the forest carbon price, the higher will be the incentive of a market-based AR programme for carbon sequestration with comparative advantages in Latin America.

The economic impacts on production are greater in forestry than in agriculture if carbon prices increase and AR programmes are not regarded (Subsection 4.4.2). The options to keep total wood production in balance with demand comprise the reduction of harvest age, thinning operations to increase volume growth and clearing of additional natural forests, which are all associated with additional unit costs of wood production per hectare and infrastructure costs to clear natural forest elsewhere. van Kooten et al. (2004) confirm that the cost of forest mitigation projects may rise significantly due to the opportunity costs of land.

The sectoral impacts of forest-based climate change mitigation stem from opportunity costs of not expanding managed land into natural forests (AD) or increasing age-class forest area (AR). There are contrasting and levelling out effects concerning economic impacts: The overestimation of opportunity costs to agricultural and forestry land users is likely, because part of the costs would actually be transferred to consumers. In contrast, opportunity costs are underestimated because the promotion of AR programmes for carbon sequestration does not take into account the economic impacts on land use from reduced ecosystem services such as changes in surface water runoff or from land degradation. The loss of biodiversity from forest plantations to society constitutes economic costs that may lead to substantial sub-optimal area allocation to forest plantations (Caparros and Jacquemont, 2003).

II Importance of technological change and managed land expansion as determinants of economic impacts

Agricultural production cost changes and foregone cost reductions mainly stem from the associated technological change in agriculture, but in an interplay with changes in land use patterns from managed land expansion. Hence, land is either allocated to agricultural land use or forest conservation (Appendix C, Tables 4 and 5). The second study broadens the scope and finds that sectoral production cost changes still strongly depend on technological changes in agriculture (Figure 4.10) but also land available to agriculture, forestry and market-based climate change mitigation programmes (Figure 4.5). Additional complexity in results is created by changes in forest management to foster volume growth and the reduction of harvest ages to a predefined minimum (Subsection 2.4.2).

The two studies on normative forest conservation and market-based climate change mitigation in forests incorporate a generalized effect. The required average crop yield changes per region and develops differently between regions. If isolated from land expansion impacts on yield development, average crop yield changes are based on historical yield levels, associated agricultural practices and costs, and investment costs of agricultural RD, and crop demand (Dietrich et al., 2013). Changes in crop yield patterns lead to shifts in inter-regional trade patterns as confirmed by Schmitz et al. (2011) and adds to the relocation of crop production and additional deforestation where cost advantages accrue (Subsection 5.1.2 for synthesis on 'leakage effect'). The generalization of results shows that forest conservation programmes require additional agricultural intensification to effectively meet a high rate of required yield increase to feed a growing population in the future particularly in Sub-Saharan Africa as confirmed by Schmitz (2012). In integrated market-based AD and AR programmes, technological change is relatively more important for keeping total production costs low than in stand-alone AD or AR programmes. This generalized result is substantiated by the land allocation theory if the mitigation of climate change is valued (Subsection 1.2.2).

The technological change in agriculture therefore signficantly reduces the threat of deforestation. However yield increase in the future will not completely prevent deforestation as confirmed by Schmitz et al. (2011). The effect of normative forest conservation policies has been demonstrated (Chapter 3) where natural forest conservation increases average crop yields but also shifts cropland expansion into other forests. Similar trends have been estimated for market-based climate change mitigation programmes in forests such as AD (Chapter 4). The general finding of a persistent strong incentive to use forest land for agriculture is consistent with Boserup (2005) who elaborates on the conditions of agricultural production growth to feed a growing population.

In contrast, yield increases may trigger deforestation (Angelsen, 2010). In relation to this, Hyde (2003) specifies that labour-substituting technological change frees labour for further deforestation activities. Lambin and Meyfroidt (2011) and Matson and Vitousek (2006) mention the rebound effect, where intensive agriculture does not spare land for nature conservation because of the displacement of marginal farmers to marginal lands, additional population growth from in-migration and negative environmental off-farm impacts.

Three policy recommendations are derived from previous findings:

1. From a global perspective, Latin America possesses a comparative advantage in establishing forest conservation areas with low economic impacts on agricultural land use. In contrast, Sub-Saharan Africa faces substantial pressure on existing natural forests and thus primarily qualifies for market-based AD programmes. As a prerequisite, the economic impacts on agriculture and forestry in terms of foregone production benefits need to be sufficiently addressed by compensation mechanisms. The comparabability and robustness of results still needs to be improved by a systematic model intercomparision, but results support an international climate policy that also enables the integration of AD in global forest carbon market-based climate change mitigation programmes.

2. The need for high rates of technological change is a prominent concern in Sub-Saharan Africa, which needs to be tackled as a general precondition for successful climate change mitigation programmes.

3. Unaccounted factors in the two studies such as labour-substituting technological change or rebound effects lead to the recommendation that agriculture in areas with low forest cover should be supported rather than agriculture near the forest frontier to reduce the threat of deforestation from agriculture.

5.1.4 Model uncertainties

Uncertainty is inherent to integrated land use modelling originating from a range of different uncertainty types and sources and the set of cause-effect relations captured (Rotmans and van Asselt, 2001). In line with the typology taken up by Rotmans and van Asselt (2001) uncertainty evolves from a) the lack of knowledge and b) the variability in the system under consideration (e.g. due to human behaviour, societal randomness and technological surpises). Walker et al. (2003) distinguish the location where uncertainty manifests, the boundaries of a system, the structural and technical uncertainty of the model, the uncertainty in data that drives the model and enters as constants. Uncertainties in model outputs stem from accumulated uncertainties in input datasets, derived technical parameters and processes employed. It is primarily the lack of knowledge in different locations which land use modellers try to overcome to reduce uncertainties.

Model inputs in MAgPIE-F are commonly observed or semi-measured datasets from FAO (FAO, 2006, 2010). They have their merits of being consistently available and having a large spatial coverage but also incorporate weaknesses as discussed by Schmitz (2012). Additional sources of inputs are observed values and expert estimations from country studies compiled in other model databases (GTM database, Sohngen and Tennity (2004)) or from other model outputs (LPJ). Derived technical parameter values are unobserved. The estimated inputs in MAgPIE-F have generally been validated by observed data, e.g. land conversion cost estimates and the roundwood production cost estimates from Sohngen and Tennity (2004) were compared to a range of case study results from different countries. Uncertainty remains from using them as time-static inputs, i.e. omitting the change in values over time, which would be desirable to be prescribed in the absense of modelling capital and labour markets explicity.

Some measure of uncertainty associated with inputs such as the population's standard deviation or the standard error in samples is commonly available. However, a comprehensive uncertainty analysis of MAgPIE is still required (Dietrich, 2011). Explicit approaches for accounting for several forms of uncertainty are to employ error propagation and sensitivity analyses (Dietrich, 2011). Schmitz (2012) makes first attempts to estimate uncertainty associated with key parameters. Therefore the current study makes a first attempt to grasp forest conservation and forestry sector-related uncertainty in MAgPIE-F explicitly. An analysis of output uncertainties due to uncertainty associated with key parameters, the forest carbon price path, the barrier-to-implementation paramter for AR and the maximum growing stock per hectare age-class forest has been conducted (Subsection 4.5.4). The impact of carbon price changes across time on outputs has been highlighted.

Uncertainties in model results are not only ascribed to propagated uncertainties from inputs and parameters but also the methodology of processing them to attain outputs. Model comparisons for averaging out uncertainties from processes in different models constitute an option to examine if the choice of inputs, parameters and processes makes a difference in model outputs.

The detection of output uncertainties from uncertainties incorporated in processes may also be achieved by the careful evaluation of predicted model outputs. They gain credibility and accuracy in predicting real-world phenomena such as the magnitude of deforestation if the spatial scale of analysis is appropriately selected, e.g. to be the regional scale. An approach to cope with uncertainties incorporated in processes is 'model calibration' (Strong and Oakley, 2014), the reduction of the discrepancy of modelled outputs to observed data by adjusting processes by calibration factors. In MAgPIE-F, for example, volume growth functions derived from LPJ allow calculating the growing stock of age-class forest at certain points in time. Matching modelled growing stocks to observed regional data from FAO required adjusting the volume growth function parameters accordingly because LPJ provides a simplified mechanism to forest establishment and parametrization of growth behaviour in monoculture. By means of scenario analyses on market-based AD and AR programmes (Chapter 4) the vector of assumed carbon prices serves as a measure to stepwise test the plausibility of emerging opportunity costs. Chapter 3 employs scenarios that have led to plausible changes in land use patterns along the gradient of productive land.

Dietrich (2011) highlights that wrong model implementations or missing links may be a source for model biases and output uncertainties. The boundaries of the system matters too (Walker et al., 2003). Explaining the uncertainty resulting from insufficient or wrong processes is not widespread in land use modelling.

The current study has identified potential sources of uncertainty from missing processes and the boundary of the system, such as

- the exclusion of implicit cost drivers of AD,
- the concept of rationally expected adaptation of land use to forest carbon market impacts,
- the missing feedback of macro-economic, socio-economic and political obstacles,
- the neglect of explicit costs of AD programmes,
- missing details on the processes behind technical parameters (barrier to implementation parameter to reflect on transaction costs, forest management bundle)

Uncertainty in the calculation of implicit costs arises from the small-scale wood use by local communities in developing regions, which does not show up in official statistics on wood consumption. However, present calculations are conservative regarding the magnitude of CO_2 emissions from natural forests, because degradation has not been included in calculations but is considerable, as shown by Houghton (2005). Furthermore, the estimated land shifts due to forest carbon markets do not necessarily match with other studies such as Sohngen et al. (1999). One reason is the applied methodology of short-term (myopic) decision making from time step to time step which, in contrast to intertemporal decision making (Sohngen et al., 1997, 1999), leads to the suboptimum allocation of land over time and thus flaws results. However, the results presented here do not claim to show the optimum time paths of climate change mitigation options via anticipated forest carbon markets, but focusses rationally expected production constraints, costs and benefits including forest carbon valuation.

The achievement of the required yield increase in all tropical regions remains uncertain. The model shows neither the macro-economic feedbacks of required agricultural investments on regional or even global consumption losses nor the real-world obstacles to technological change implementation (bad governance, insecure land tenure rights, limited variable production inputs). The socio-economic and political obstacles which are not modelled may jeopardize the success of forest conservation and forest carbon sequestration programmes and therefore further increase sectoral costs. However, Thomson et al. (2010) confirm the necessity of substantial future increases in agricultural productivity throughout the century to be indispensable to offset the loss of tropical forests for cropland expansion. The study also found that the preservation of tropical forests at their present day spatial extent and the use of bioenergy crops as an effective mitigation option are only possible if climate policies enable the creation of an economic value of avoided land-use emissions (Thomson et al., 2010).

Additional uncertainty is attached to neglecting explicit costs for the design, implementation, monitoring, enforcement, verification and certification of AD projects and adding so-called transaction costs to forest carbon conservation or sequestration programmes (Kindermann et al., 2006, 2008; Cacho et al., 2005; Grieg-Gran, 2006; Sathaye and Andrasko, 2007; Nepstad et al., 2007, 2009) on top of the implicit costs of AD. This underpins global climate change mitigation through AD to remain a relative low-cost option from a society's perspective (Kindermann et al., 2008), even though only the sectoral opportunity costs have been calculated in this study. Forest carbon finance could come from the transport or energy sector to offset CO_2 emissions once AD is eligible in regulated forest carbon markets. However, it is likely that the costs of AD will be transferred to end consumers. If the explicit costs of AD were substantial and thus taken into account, the carbon mitigation supply curve would shift to the left, i.e. agricultural and forestry sectors 'produce' less CO_2 emission mitigation. Up to an assumed carbon price the total quantity of avoided CO_2 emissions would be decreased, i.e. the emission mitigation benefit to society would be less. Cacho et al. (2005) make a more thorough investigation, including carbon market effects of transaction and abatement costs of carbon sequestration projects in developing countries.

In the case of Sub-Saharan Africa, it is reasonable to assume that relatively low implicit costs of AD may be offset by relatively high transaction costs to promote effective forest conservation given the high rates of required technological change in agriculture, the foregone forestry commodities obtained from natural forests, the forest tenure generally held by states (Hatcher and Bailey, 2011)[1] in connection with bad governance in forest carbon emitting countries (Hatcher and Bailey, 2011; Mo, 2001)[2]. Although the present study neglects transaction costs and thus the CO_2 emissions mitigation estimates would be lower, the estimates are conservative because only aboveground and belowground living biomass have been regarded.

The success of AD beyond the economic potential depends on a series of additional factors not included in this thesis which puts the results into perspective. Fearnside (2000) identifies that the high potential of AD is associated with high uncertainty in estimates, because its agents, drivers, and underlying causes are much less understood (or more difficult to be modelled) than for AR activities. The economic potential estimates for AD in tropical regions do not reflect on the ownership of forests (Angelsen, 2010) and the devolution of forest management to local communities (Chhatre and Agrawal, 2009), which may help to achieve the goal of forest conservation through payments for carbon storage. As a further prerequisite to reach the economic potential, the leakage and additionality arguments have been discussed. However, since dynamic pasture area development is not allowed in the model, the displacement of wood and crop production activities to pasture area may lead to downward shifts in the magnitude of net avoided carbon emissions from land use change.

The performed uncertainty analysis in MAgPIE-F is only a very first exercise to grasp uncer-

[1] According to Hatcher and Bailey (2011, p.320) 98 % of forests in Africa are administered by governments in contrast to a significantly lower share in Latin America and Asia.

[2] In Sub-Saharan Africa, the Democratic Republic of Congo, Nigeria, Zambia are listed by Hatcher and Bailey (2011, p.319) among the ten forest carbon emitting countries with low corruption index value, i.e. bad governance, which influences the share of private investment towards innovations and the investment to GDP ratio (Mo, 2001).

tainties. Further studies on the systemic identification of key inputs and parameters as well as the means to analyse inherent uncertainties and accumulated output uncertainties via Monte Carlo analyses or Gaussian quadratures are needed (Dietrich, 2011). Schmitz (2012, p.109) already notes that 'for models like MAgPIE, with many different input parameters and complex processes, it will be a huge but necessary effort'. A most recent agro-economic model comparison exercise included MAgPIE and tackled process uncertainties in the model for the first time, although without the forestry sector dynamics (Schmitz et al., 2014).

5.2 Suggestions for further research

The need for future research has been identified from the present version of MAgPIE-F and current model applications. Chapter 2 deals with the conceptual extensions of the land use optimization model MAgPIE to incorporate the forestry sector. From a technical perspective, the forestry sector needs further improvements.

Further elaboration and refinement on representing the demand for wood products is needed (Subsection 2.3.3). The presented approach is relatively coarse for a range of wood products in terms of input to output coefficients, self-sufficiency shares and the substitution of intermediates in end products, the functional forms of demand models, and the robustness of projections. The introduction of variance functions could serve as a remedy to the heteroscedasticity of variances in mixed effect models which is suggested as a means to improve demand projections.

Taking the employed mechanisms on rationally expectated wood demand and supply as a starting point, further studies are recommended to consider technological change in forestry and uncertainty in production decisions created by unexpected wood losses from environmental threats such as forest fires.

The introduced model version treats wood as a homogenous commodity harvested from the merchantable growing stock. However the share of producible assortments per hectare in different forest types is needed. The introduction of thinning intensity as a management tool changes the relative composition of assortments. This could be helpful to investigate production shifts to sawlogs, where higher diameter dimensions are needed. Forest productivity increase needs to be implemented explicitly to reflect on more realistic competition for land.

Further recommendations are derived from Chapter 4 and comprise a comprehensive sensitivity analysis to comprise input, parameter and process uncertainties pertaining to biological growth, agricultural and forestry yields, forest management such as rotation length, and intensity of thinning as well as sectoral production and transport costs.

Longer rotations of age-class forests (> 30 years) may unveil the effect of decreasing competitiveness of agriculture for land relative to forestry. The assumption may hold due to exponentially increasing net benefits from forest carbon payments up to the inflection point (species-specific) until the growth of age-class forest volume diminishes. From a different perspective, the economic potential of carbon sequestration in age-class forest should decrease with decreasing rotation length which requires further research.

It is recommended that a model comparison is conducted which incorporate multiple land use sectors to check the performance of MAgPIE-F regarding the mitigation potential and sectoral impacts of comparable carbon price scenarios.

In MAgPIE-F, the infrastructure network and transport mode, i.e. the time needed to reach a market, is static and may be improved by simulating urban expansion and prescribed transport mode transitions. It is recommended to develop a time-dynamic version of the infrastructure network since transport costs have been proven to contribute a considerable share to opportunity costs.

Furthermore, the global perspective of MAgPIE-F may lead to an overestimation of the mitigation potential similar to that stated in IPCC AR4 (Metz et al., 2007; Nabuurs and Masera, 2007) and Kremen et al. (2000). Therefore, further research is recommended on higher-resolution regional scale applications. Additional in-depth studies are needed to cover the analysis of transaction cost, suboptimum levels of investments in agricultural RD and refined carbon density estimates.

The livestock sector and land demand for grazing and fodder production needs to be accounted for since livestock herding contributes to forest degradation in developing countries and countries in transition. In the Amazon basin the predisposition of deforestation is laid by cattle ranger and the encroachment of frontier forest for grazing predominantly (Malhi et al., 2008). Related to land use for feed, fodder and pastures, it is recommended to test the model functionality with full mobility of land across crop, livestock and forestry sectors.

Appendix A: Mathematical description of MAgPIE

Introduction

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a nonlinear recursive dynamic optimization model that links regional economic information with grid-based biophysical constraints simulated by the dynamic vegetation model LPJmL. The basic mathematical description of MAgPIE has been adapted from Dietrich (2011, Section 2.3).

A simulation run with the simulation period T can be described as a set

$$X = \{x_t \mid t \in T\} \subseteq \Omega \tag{1}$$

of solutions of a time depending minimization problem, i.e. for every timestep $t \in T$ the following constraint is fulfilled

$$\forall y \in \Omega : g_t(x_t) \leq g_t(y) \tag{2}$$

where the goal function for $t \in T$

$$g_t(x_t) = g(t, x_t, x_{(t-1)}, ..., x_1, P_t) \tag{3}$$

depends on the solutions of the previous time steps $x_{(t-1)}, ..., x_1$ and a set of time depending parameters P_t. A MAgPIE simulation run $X = \{x_t \mid t \in T\} \subseteq \Omega$ may be interpreted as an element of the vector space $\Omega_T = \Omega \times T$.

Sets

The dimension of the domain Ω, on which for each timestep the minimization problem is defined, and $dim\Omega_T$ depends on the following sets:

- $T = \{\text{time steps } t\}$: Simulation time steps, where t denotes the current time step, $t-1$ the previous time step and so on. The first simulated time step is $t = 1$.
- $I = \{\text{world regions } i\}$: Economic world regions in MAgPIE.
- $J = \{\text{spatial clusters } j\}$: Highest spatial disaggregation level in MAgPIE.
- $K = \{\text{simulated products } k\}$: Union of vegetal products V and livestock products L ($K = V \cup L$).
- $L = \{\text{simulated livestock products } l\}$: Products simulated within the livestock sector of MAgPIE.

- $V = \{\text{vegetal products } v\}$: Products simulated within the crop sector of MAgPIE.
- $W = \{\text{water supply types } w\}$: Currently two types are implemented: rainfed 'rf' and irrigated 'ir'
- $C = \{\text{crop rotation groups } c\}$: Groups of crops, which have similar requirements concerning crop rotation criteria.

To highlight the substance of the model equations with regard to the agricultural and economic contents, the variable x_t is split into

$$x_t = \left(x_t^{area} \in \Omega^{area}, x_t^{prod} \in \Omega^{prod}, x_t^{tc} \in \Omega^{tc}\right) \in \Omega \tag{4}$$

where the respective domains can be identified as the following vector spaces

$$\begin{aligned} \Omega^{area} &= \mathbb{R}^{|J|} \times \mathbb{R}^{|V|} \times \mathbb{R}^{|W|} \\ \Omega^{prod} &= \mathbb{R}^{|J|} \times \mathbb{R}^{|L|} \\ \Omega^{tc} &= \mathbb{R}^{|I|} \end{aligned} \tag{5}$$

As a result, the dimension of the solution space for each timestep may be specified as $dim\Omega = |J| \cdot |V| \cdot |W| + |J| \cdot |L| + |I|$ and the dimension of $\Omega_T = \Omega \times T$ as $dim\Omega_T = |T| \cdot dim\Omega = |T| \cdot (|J| \cdot |V| \cdot |W| + |J| \cdot |L| + |I|)$. In the following sections, variables and parameters are provided with subscripts to indicate the dimension of the respective subdomains. Subscripts written in quotes are single elements of a set. The order of subscripts in the variable, parameter and function definitions does not change. The names of variables and parameters are written as superscript.

Variables

MAgPIE is a recursive dynamic optimization model and all variables refer to a certain time step $t \in T$. In each optimization step, only the variables belonging to the current time step are free variables. For all previous time steps, values were fixed in earlier optimization steps. As indicated above, three variables $x_t^{area} \in \Omega^{area}$, $x_t^{prod} \in \Omega^{prod}$ and $x_t^{tc} \in \Omega^{tc}$ are distinguished that can be described as follows:

- $x_{t,j,v,w}^{area}$: The total area of each vegetal production activity v for each water supply type w, each cluster j and each time step t [ha]
- $x_{t,j,l}^{prod}$: The total production of each livestock product l, for each cluster j at each time step t [ton dry matter]
- $x_{t,i}^{tc}$: The amount of yield growth triggered by investments in R&D [-]

Parameters

The model is contains a set of parameters P_t. These parameters are computed exogenously and are in contrast to variables of previous time steps fully independent of any simulation output. Although most parameters are time independent, there are some parameters which are time dependent.

- $p^{yield}_{t,j,v,w}$: Yield potentials for each time step, each cluster, each crop and each water supply type taking only biophysical variations into account and excluding changes due to technological change [ton/ha]
- $p^{dem}_{t,i,k}$: Regional food and material demand in each time step for each product [10^6 ton]
- $p^{fbask}_{i,l,k}$: Feed basket parameter describing the share of each product k in the feed basket related to livestock product l and corresponding transformation from GJ feed in ton dry matter [ton/GJ]
- $p^{feed}_{i,l}$: Feed requirements for each livestock product l in each region i [GJ/ton]
- $p^{byprod}_{i,k,l}$: Feed energy delivered by the byproducts of k that are avaiable as feedstock for the livestock product l [GJ/ton]
- $p^{frv}_{i,v}$: Area related factor requirements for each crop and each region based on the technological development level in the initial time step [US$/ha]
- $p^{frl}_{i,l}$: Production related factor requirements for livestock products for each livestock type and each region [US$/ton]
- p^{lcc}_{i}: Area related land conversion costs for each region [US$/ha]
- p^{tcc}: Technological change cost factor accounting for interest rate, expected lifetime and general costs [US$/ha]
- $p^{\tau 1}_{i,v}$: τ-Factor representing the agricultural land use intensity in the first simulation time step for each crop in each region [-]
- p^{cxp}: Correlation Exponent between τ-Factor and technological change costs [-]
- $p^{seed}_{i,v}$: Share of production that is used as seed for the next period calculated for each crop in each region [-]
- $p^{xs}_{t,i,k}$: Regional excess supply for each product and each time step describing the amount produced for export [10^6 ton]
- $p^{sf}_{i,k}$: Regional self sufficiencies for each product [-]
- p^{tb}: Trade balance reduction factor with $0 \leq p^{tb} \leq 1$ which is used to relax the trade balance constraints depending on the particular trade scenario.
- $p^{land}_{t,j}$: Total amount of land available for crop production in each cluster [10^6 ha]
- $p^{ir.land}_{j}$: Total amount of land equipped for irrigation in each cluster [10^6 ha]
- $p^{watreq}_{j,k}$: Cluster-specific water requirements for each product [$m^3/ton/a$]
- p^{water}_{j}: Amount of water available for irrigation in each cluster [$m^3/ton/a$]

- p_c^{rmax}: Maximum share of crop groups in relation to total agricultural area [-]
- p_c^{rmin}: Minimum share of crop groups in relation to total agricultural area [-]

[all ton units are in dry matter]

Sub-Functions

To simplify the general model structure, some model components which appear more than once in the model description and depend on the variables of the current time step t are arranged as functions:

$$
\begin{aligned}
f_{t,i}^{growth}(x_t) &= \prod_{\tau=1}^{t}\left(1 + x_{\tau,i}^{tc}\right) \\
f_{t,i,k}^{prod}(x_t) &= \sum_{j_i} \begin{cases} x_{t,j,k}^{prod} & : k \in L \\ \sum_w x_{t,j,k,w}^{area} p_{t,j,k,w}^{yield} f_{t,i}^{growth}(x_t) & : k \in V \end{cases} \\
f_{t,i,k}^{dem}(x_t) &= p_{t,i,k}^{dem} + \sum_l p_{i,l,k}^{fbask}\left(p_{i,l}^{feed} f_{t,i,l}^{prod}(x_t) - \sum_\kappa p_{i,\kappa,l}^{byprod} f_{t,i,\kappa}^{prod}(x_t)\right)
\end{aligned} \tag{6}
$$

- $f_{t,i}^{growth}$: Growth function describing the aggregated yield amplification due to technological change compared to the level in the starting year for each year t and region i.
- $f_{t,i,k}^{prod}$: Function representing the total regional production of a product k in region i at timestep t. In the case of vegetal products, it is derived by multiplying the current yield level with the total area used to produce this product. In the case of livestock products, it is represented by the related production variable.
- $f_{t,i,k}^{dem}$: Function defining the demand for product k in region i at timestep t. It consists of an exogenous demand for food and materials $p_{t,i,k}^{dem}$ and an endogenous demand for feed, which is calculated as the feed demand generated by the livestock production minus the feed supply gained through byproducts.

Goal Function

$$g_t(x_t) = g(t, x_t, x_{(t-1)}, ..., x_1, P_t) \tag{7}$$

The goal function describes the value that is minimized in the recursive dynamic optimization model in each timestep. It is time dependent, i.e. it differs for each time step, depending on the solutions of the previous time steps. The goal function is defined as follows:

$$
\begin{aligned}
g_t(x_t) = & \sum_{i,v} \left(p^{frv}_{i,v} f^{growth}_{t,i}(x_t) \sum_{j_i,w} x^{area}_{t,j,v,w} \right) \\
& + \sum_{i,l} \left(p^{frl}_{i,l} f^{prod}_{t,i,l}(x_t) \right) \\
& + \sum_{i} \left(p^{lcc}_{i} \sum_{j_i,v,w} \left(x^{area}_{t,j,v,w} - x^{area}_{t-1,j,v,w} \right) \right) \\
& + p^{tcc} \sum_{i} \left(x^{tc}_{t,i} \left(\frac{1}{|V|} \sum_{v} p^{\tau 1}_{i,v} f^{growth}_{t,i}(x_t) \right)^{p^{cxp}} \sum_{j_i,v,w} x^{area}_{t-1,j,v,w} \right)
\end{aligned}
\tag{8}
$$

The function describes the total costs of agricultural production. The total costs can be split into four terms: 1. area depending factor costs of vegetal production, which increase with the yield gain due to technological change; 2. factor costs of livestock production depending on the production output; 3. land conversion costs which arise, when non-agricultural land is cleared and prepared for agricultural production; 4. investment costs in technological change to increase yields by improvements in management strategies and other inventions. The technological change costs are proportional to total cropland area of a region and increase disproportionately with yield growth bought in the current timestep and the agricultural land-use intensity.

Constraints

Constraints describe the boundary conditions, under which the goal function is minimized.

Global demand constraints

$$
\sum_{i} \frac{f^{prod}_{t,i,k}(x_t)}{1 + p^{seed}_{i,k}} \geq \sum_{i} f^{dem}_{t,i,k}(x_t), \; \forall \; k \in K
\tag{9}
$$

These constraints describe global demand for agricultural commodities: Total production of a commodity k adjusted by the seed share required for the next production iteration has to meet the demand for this product.

Trade balance

$$
\frac{f^{prod}_{t,i,k}(x_t)}{1 + p^{seed}_{i,k}} \geq p^{tb} \begin{cases} f^{dem}_{t,i,k}(x_t) + p^{xs}_{t,i,k} & : p^{sf}_{i,k} \geq 1 \\ f^{dem}_{t,i,k}(x_t) p^{sf}_{i,k} & : p^{sf}_{i,k} < 1 \end{cases}, \; \forall \; i \in I, \; \forall \; k \in K
\tag{10}
$$

The trade balance constraints are similar to the global demand constraints, except that they act on a regional level. In the case of an exporting region (self sufficiency for the product k is greater than 1), the production has to meet the domestic demand supplemented by the demand caused due to export. In the case of importing regions (self sufficiency less than 1), the domestic demand is multiplied with the self sufficiency to describe the amount which has to be produced by the region itself. In both cases the demand is multiplied with a so called 'trade balance reduction factor'. This factor is always less than or equal to 1 and is used to relax the trade balance constraints depending on the particular trade scenario for the future.

Land constraints

$$\begin{aligned}\sum_{v,w} x^{area}_{t,j,v,w} &\leq p^{land}_{j}\\ \sum_{v} x^{area}_{t,j,v,'ir'} &\leq p^{ir.land}_{j},\ \forall\ j \in J\end{aligned} \tag{11}$$

The land constraints guarantee that no more land is used for production than available. The first set of land constraints ensures the land availability for agricultural production in general. The second one secures that irrigated crop production is restricted to areas that are equipped for irrigation.

Water constraints

$$\sum_{v} x^{area}_{t,j,v,'ir'} p^{yield}_{t,j,v,'ir'} f^{growth}_{t,i(j)}(x_t) p^{watreq}_{j,v} + \sum_{l} x^{prod}_{t,j,l} p^{watreq}_{j,l} \leq p^{water}_{j},\ \forall\ j \in J \tag{12}$$

The output of animal products as well as vegetal products under irrigated conditions requires water. The required amount of water is proportional to the production volume. The whole water demand in each cluster must be less or equal to the water available for production in this cluster.

Rotational constraints

$$\begin{aligned}\sum_{v_c} x^{area}_{t,j,v,w} &\leq p^{rmax}_{c} \sum_{v} x^{area}_{t,j,v,w}\\ \sum_{v_c} x^{area}_{t,j,v,w} &\geq p^{rmin}_{c} \sum_{v} x^{area}_{t,j,v,w},\ \forall\ c \in C,\ \forall\ j \in J,\ \forall\ w \in W\end{aligned} \tag{13}$$

The rotational constraints are used to prescribe typical crop rotations by defining for each vegetal product a maximum and minimum share relative to total area under production in a cluster.

Appendix B: Supplementary material to 'Model extensions' (Chapter 2)

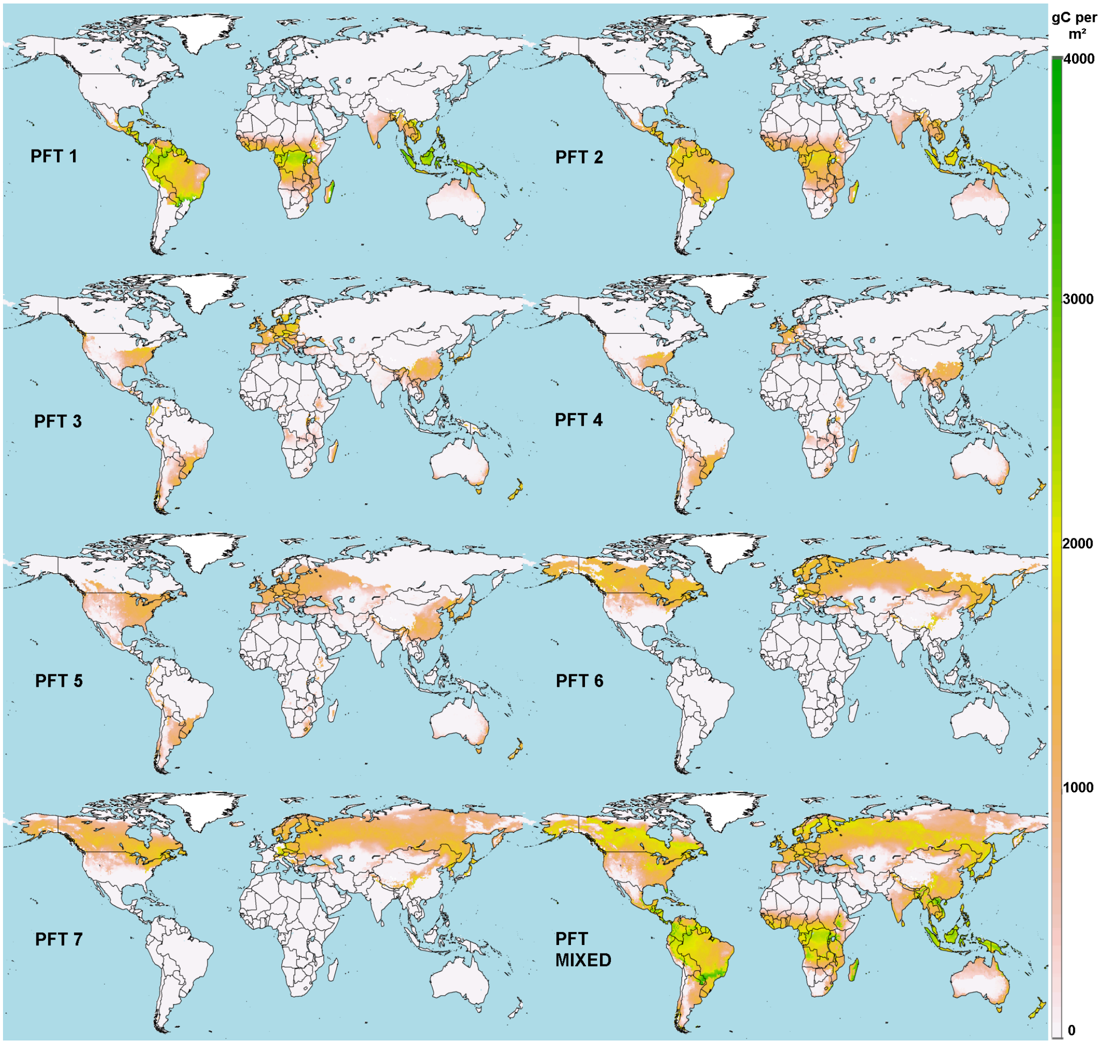

Figure 1: LPJ-generated vegetation carbon stock in Plant Functional Types (PFTs) at age 200 [gC per m^2], supplementary material to Subsection 2.3.1

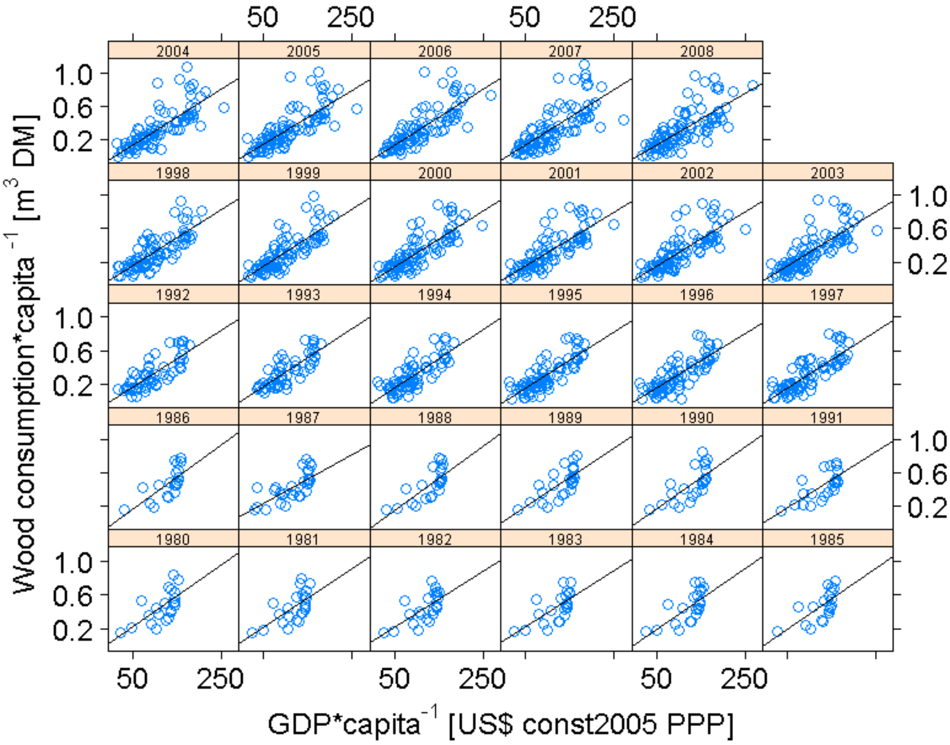

Figure 2: SVP consumption per capita and GDP per capita 1980 - 2008

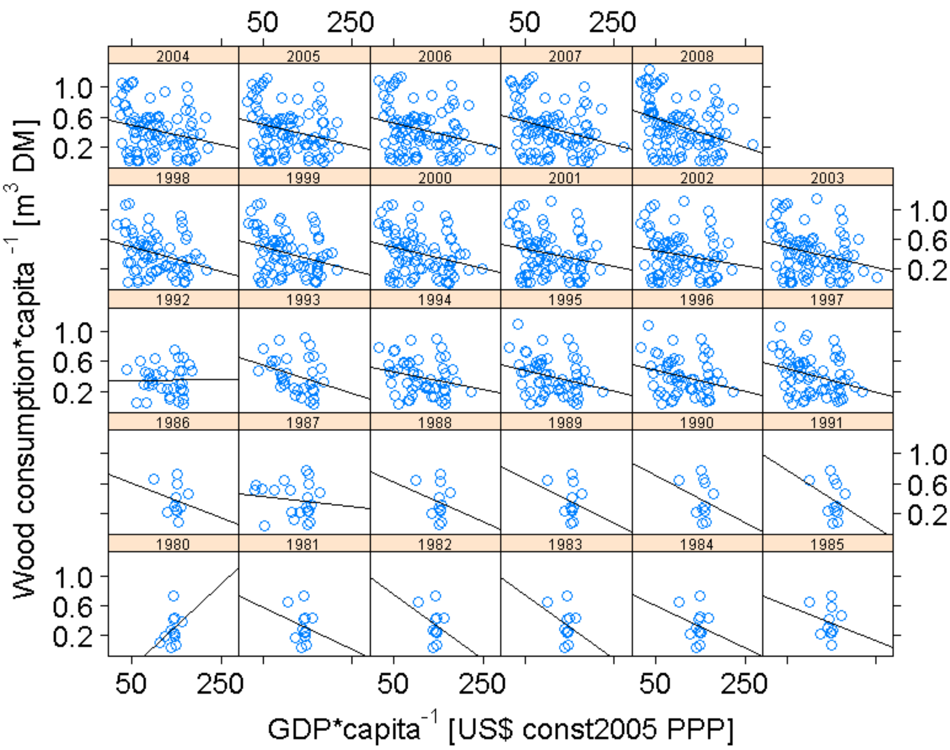

Figure 3: WF consumption per capita and GDP per capita 1980 - 2008

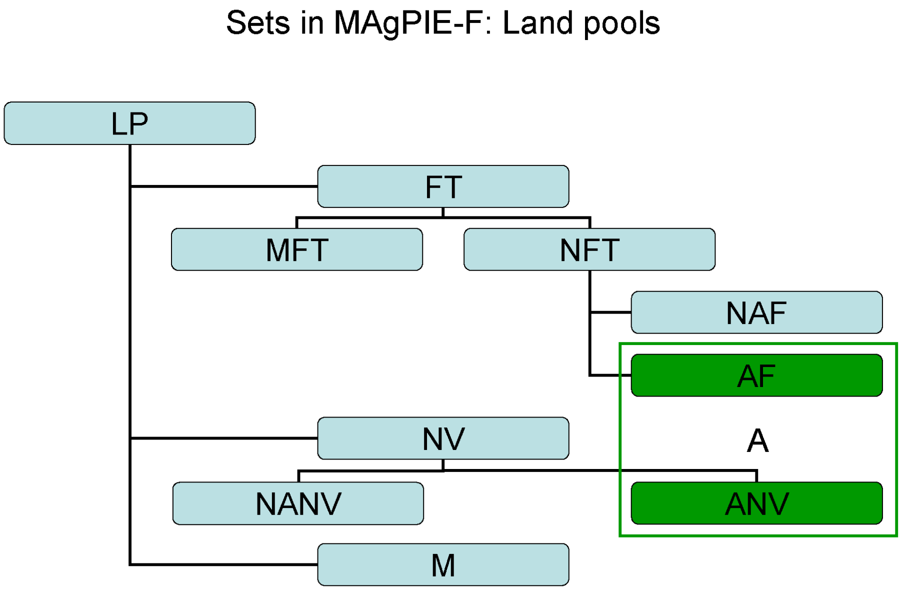

Figure 4: Relationship of sets denoting land pools in MAgPIE-F, supplementary material to Subsection 2.4.2

Table 1: Employed geographic datasets in spatial data integration for land use database, supplementary material to Subsection 2.2.2

Type of dataset	Name of dataset	Year	Spatial resolution, Projection, Coverage	Category employed	Institution	Reference
Land use	Land use data set for the year 2000	2000	5 arc min. res., geographic projection, 90° to -90° lat, -180° to 180° lon	all	Institute of Social Ecology, Klagenfurt University	Erb et al. (2007)
Land suitability	Suitability of global land area for rain-fed crops using max. crop and tech. mix	2002, 2005	5 arc min. res., geographic projection, 90° to -90° lat, -180° to 180° lon	SI0, SI5, SI40, SI85	FAO, IIASA	Fischer et al. (2002), van Velthuizen (2007)
Protected areas	Protected areas National	2004	Polygons, geographic projection, 90° to -90° lat, -180° to 180° lon	Category I, II	UNEP-WCMC	UNEP-WCMC (2004)
Intact forest	World intact forest landscapes map	2005	Polygons, geographic projection, 69° to -55° lat, -172° to 178° lon	all	Greenpeace International	Greenpeace (2005)
Frontier forest	The last frontier forests	1997	Polygons, pseudo-cylindrical equal area projection, 7984568m, -6417752, -10138882, 15316100m	all	WRI	Bryant et al. (1997)
Land use	Rain-fed, irrigated cropland and managed grassland	1700 to 2005	30 arc sec res., 90° to -90° lat, -180° to 180° lon	Cropland 2000	Potsdam Institute for Climate Impact Research	Fader et al. (2010)
Land cover	The global land cover map for the year 2000	2000	32.1 arc sec res., geographic projection, -89.99° to 56.01° lat, -180° to 179.99° lon	Category 37 (Snow)	European Commission Joint Research Centre	Fritz et al. (2003)

Appendix C: Supplementary material to 'Conservation of undisturbed natural forest and economic impacts on agriculture' (Chapter 3)

Supplementary results

Table 2: Initialized land pools in 1995 (Million ha)

Economic region	Cropland	% of total	Pool of available land			
			IFF	% of total	Other land	% of total
AFR	192	7.9	108	4.5	21	0.9
LAM	153	7.6	487	24.2	25	1.2
PAS	80	22.5	77	21.7	2	0.6
ROW	1021	12.7	62	0.8	74	0.9
World	1446	11.2	734	5.7	122	0.9

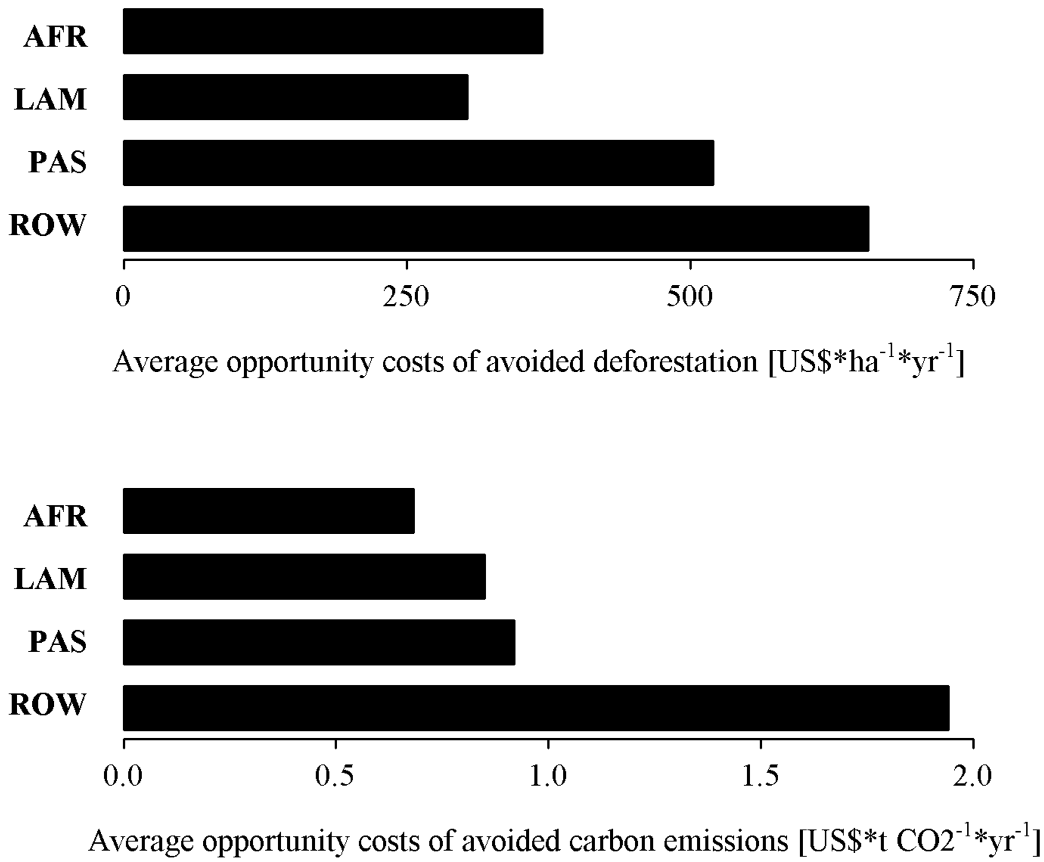

Figure 5: Average annual opportunity costs, FC100 versus BAU, 2015 to 2055

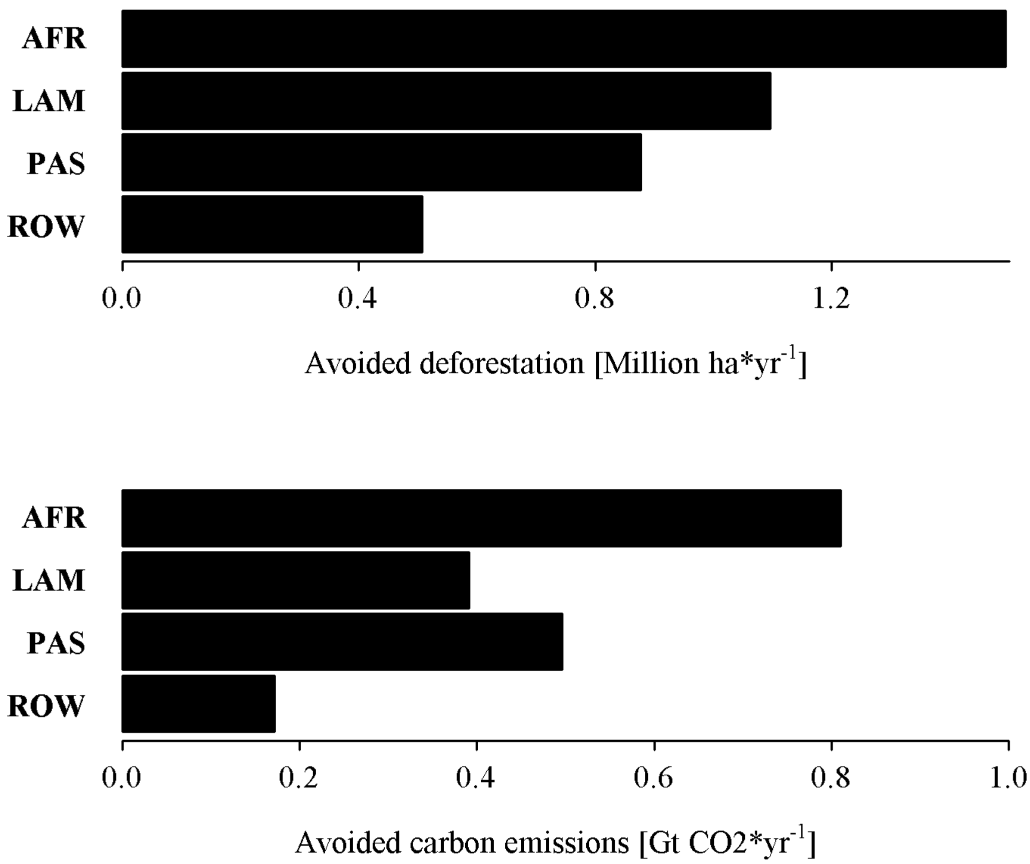

Figure 6: Avoided deforestation and avoided net carbon emissions, FC100 versus BAU, 2015 to 2055

Table 3: Disaggregation of total opportunity costs by cost types (Million US$ per year), 2015 to 2055

Economic region	Factor costs (1)			RD costs (2)			Land conversion costs (3)			Transport costs (4)			$\sum$		
	FC100	FC50-Y	FC50-C	FC100	FC50-Y	FC50-C	FC100	FC50-Y	FC50-C	FC100	FC50-Y	FC50-C	FC100	FC50-Y	FC50-C
AFR	0.00	0.00	0.07	0.88	0.12	0.20	-0.28	-0.05	-0.09	-0.04	0.03	-0.03	0.55	0.10	0.15
LAM	-0.07	-0.04	0.01	0.66	0.34	0.08	-0.27	-0.16	-0.04	0.00	-0.06	-0.04	0.33	0.07	0.00
PAS	-0.04	-0.01	0.04	0.71	0.11	0.08	-0.21	-0.04	-0.03	0.00	-0.01	-0.03	0.46	0.05	0.05
ROW	-0.03	-0.01	0.01	0.65	0.07	0.14	-0.15	-0.02	-0.03	-0.13	0.00	-0.02	0.33	0.04	0.09
World	-0.14	-0.07	0.13	2.90	0.64	0.50	-0.91	-0.26	-0.20	-0.18	-0.04	-0.13	1.67	0.26	0.30

Table 4: Projected annual change in land pools (Million ha per year), 2015 to 2055

Economic region	Time period	Cropland				Available IFF				Conserved IFF				Other available land			
		BAU	FC100	FC50-Y	FC50-C	BAU	FC100	FC50-Y	FC50-C	BAU	FC100	FC50-Y	FC50-C	BAU	FC100	FC50-Y	FC50-C
	2015	3.5	2.5	2.5	2.5	-1.0	-7.5	-0.7	-0.7	nil	7.5	0.7	0.7	-2.5	-2.5	-2.5	-2.5
AFR	2055	2.8	0	0	0	0	0	0	0	nil	0	0	0	-2.8	0	0	0
	Mean	3.1	1.6	2.7	2.6	-1.5	-1.5	-1.5	-1.5	nil	1.5	0.4	0.5	-1.6	-1.6	-1.6	-1.6
	2015	0.9	0.1	0.3	1.7	-0.9	0	-4.9	-6.3	nil	46.9	4.7	4.7	-0.1	-0.1	-0.1	-0.1
LAM	2055	1.6	0	1.5	1.6	0	0	-6.0	-5.8	nil	0	6.0	5.8	-1.6	0	-1.5	-1.6
	Mean	1.6	0.6	1.2	1.5	-1.1	-9.4	-6.0	-6.2	nil	9.4	5.3	5.2	-0.5	-0.6	-0.5	-0.5
	2015	0.7	0.1	0.4	0.4	-0.6	-6.4	-0.9	-0.9	nil	6.4	0.6	0.6	-0.1	-0.1	-0.1	-0.1
PAS	2055	1.2	0	0	1.0	-1.2	0	-0.3	-1.1	nil	0	0.3	0.4	0	0	0	-0.2
	Mean	0.9	0.1	0.7	0.8	-0.9	-1.3	-1.1	-1.2	nil	1.3	0.5	0.5	0	-0.1	0	-0.1
	2015	2.5	1.8	2.5	2.4	-0.7	-3.3	-1.0	-0.9	nil	3.3	0.3	0.3	-1.8	-1.8	-1.8	-1.8
ROW	2055	1.0	0.3	0.2	0.7	-0.7	0	-0.1	-0.6	nil	0	0.1	0.2	-0.3	-0.3	-0.2	-0.3
	Mean	1.1	0.6	1.0	1.0	-0.5	-0.7	-0.6	-0.6	nil	0.7	0.2	0.3	-0.6	-0.6	-0.6	-0.6
	2015	7.6	4.6	5.7	7.0	-3.1	0	-7.6	-8.9	nil	64.1	6.4	6.4	-4.5	-4.6	-4.5	-4.5
World	2055	6.6	0.3	1.7	3.2	-1.8	0	-6.4	-7.5	nil	0	6.4	6.4	-4.7	-0.3	-1.7	-2.1
	Mean	6.7	2.9	5.5	5.9	-4.0	0	-9.2	-9.5	nil	12.8	6.4	6.4	-2.7	-2.9	-2.7	-2.8

Table 5: Projected annual change in crop yield level due to R&D input (% per year), 2015 to 2055

Economic region	Time period	Scenario			
		BAU	FC100	FC50-Y	FC50-C
AFR	2015	1.0	1.5	1.5	1.5
	2055	0.8	1.8	1.6	1.3
	Mean	1.2	1.8	1.3	1.4
LAM	2015	1.4	1.8	1.8	1.0
	2055	0.4	1.0	0.4	0.4
	Mean	0.7	1.3	1.0	0.8
PAS	2015	1.1	1.7	1.4	1.4
	2055	0.1	1.1	1.0	0.3
	Mean	0.7	1.5	0.9	0.9
ROW	2015	1.4	1.4	1.4	1.4
	2055	0.6	0.6	0.6	0.6
	Mean	1.1	1.1	1.1	1.1
World	2015	1.3	1.5	1.4	1.3
	2055	0.5	0.9	0.7	0.6
	Mean	1.0	1.3	1.1	1.1

Table 6: Projected annuity of agricultural cost types in BAU (Billion US$ per year), 2015 to 2055

Economic region	Factor costs	RD costs	Land conversion costs	Transport costs
AFR	11.53	1.29	1.18	3.43
LAM	12.90	0.83	0.85	3.27
PAS	8.81	0.67	0.43	3.44
ROW	85.20	17.55	0.90	15.72
World	118.43	20.34	3.36	25.86

Table 7: Projected annual change in cost types compared to BAU (% per year), 2015 to 2055

Economic region	Factor costs			RD costs			Land conversion costs			Transport costs		
	FC100	FC50-Y	FC50-C	FC100	FC50-Y	FC50-C	FC100	FC50-Y	FC50-C	FC100	FC50-Y	FC50-C
AFR	0	0	0	0.7	0.1	0.2	-0.2	0	-0.1	0	0	0
LAM	0	0	0	0.8	0.4	0.1	-0.3	-0.2	-0.1	0	0	0
PAS	0	0	0	1.1	0.2	0.1	-0.5	-0.1	-0.1	0	0	0
ROW	0	0	0	0	0	0	-0.2	0	0	0	0	0
World	0	0	0	0.1	0	0	-0.3	-0.1	-0.1	0	0	0

Appendix D: Baseline and other outputs of MAgPIE-F

Baseline outputs of MAgPIE-F

The regional and global average percentage values of technological change are underlying for the calculation of difference values in percentage points per year for each of the carbon market scenarios in Chapter 4.

Table 8: Baseline average technological change rates in agriculture from 2010 to 2100 [% per year]

Economic region	Value
AFR	0.58
LAM	0.34
PAS	0.29
ROW	0.74
Global	0.59

The regional and global average land conversion rates are underlying for the calculation of difference values in million hectares per year for each of the carbon market scenarios in Chapter 4.

Table 9: Baseline average land conversion rates from 2010 to 2100 [Mha per year]

Economic region	Cropland	Managed grassland & rangeland	Age-class forest	Potentially managed natural forest	Undisturbed natural forest	Unused other natural vegetation
AFR	3.50	0.07	0.06	-2.33	-1.15	-0.15
LAM	2.33	0.01	0.20	-1.94	-0.52	-0.09
PAS	0.86	-0.01	0.08	-0.27	-0.65	-0.01
ROW	0.68	-0.08	1.88	-1.49	-0.30	-0.68
Global	7.37	-0.02	2.22	-6.03	-2.62	-0.93

The annual baseline deforestation rate in global forests exceeds the historical deforestation rate of global forests. The two model applications (Chapter 3 and Chapter 4) are contrasted for comparable time steps from 2015 to 2055.

The projected baseline AR area (Table 11) can be contrasted to the historically observed area (Table 2.3). The yearly values provided for the time steps 2005 to 2095 constitute average values per decade from 2000 to 2100.

Table 10: Baseline magnitude of deforestation, modelled future values versus observed historical values [Mha per year]

Forest type	Magnitude of baseline deforestation [Mha per year]		
	1990 to 2010 FAO (2010)	2015 to 2055 MAgPIE	2015 to 2055 MAgPIE-F
Primary forest / Undisturbed natural forest	4.1	4.0	2.8
Other forest (excl. age-class forest)			5.9
Global forest	6.8	4.0	8.7

Table 11: Baseline regional afforestation / reforestation area of age-class forest [Mha per year]

Year	Afforestation / reforestation area per region [Mha per year]									
	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	2.1	24.4	3.1	2.0	6.3	0.7	5.9	0.7	1.8	3.3
2015	2.7	22.0	2.8	1.8	5.7	0.8	5.4	0.7	1.7	3.0
2025	1.8	19.8	2.5	1.6	5.1	1.0	4.8	0.6	1.6	2.7
2035	1.5	17.8	2.2	1.5	4.6	1.5	4.3	0.5	1.5	2.7
2045	1.4	16.0	2.0	1.3	4.1	1.6	3.9	0.5	1.4	3.3
2055	1.2	14.4	1.8	1.2	3.7	3.9	3.5	0.4	1.3	2.7
2065	1.1	13.0	1.6	1.1	3.3	1.9	3.2	0.4	1.6	2.8
2075	1.0	11.7	1.5	1.0	3.0	3.8	2.8	0.3	1.5	3.0
2085	0.9	10.5	1.3	0.9	2.7	1.9	2.6	0.3	1.3	3.1
2095	0.8	9.5	1.2	0.9	2.4	2.3	2.3	0.3	1.5	3.2

Table 12: Baseline global net production of wood commodities in global forests (excluding harvest losses) [Million m^3 Dry Matter per year]

Year	Wood production in global forests [Million m^3 Dry Matter per year]			
	Saw & Veneer logs	Pulp logs	Other industrial roundwood	Woodfuel
2005	1338	206	1849	202
2015	1586	236	1859	221
2025	1807	267	1890	239
2035	1983	299	1907	253
2045	2130	334	1874	263
2055	2209	367	1840	270
2065	2210	400	1813	274
2075	2157	432	1788	276
2085	2061	468	1775	278
2095	1924	506	1761	278

The global baseline production of wood commodities net of harvest losses is shown hereafter, taking all forest types (Table 12) and age-class forest into consideration (Table 13).

The regional baseline production and consumption of wood in roundwood equivalents is shown hereafter.

Supplementary material to Chapter 4

The dynamics of land use changes and impact of carbon price scenarios over time has been illustrated for the baseline (no carbon price), and scenarios on carbon prices of 11, 55 and 110 US$ per ton CO_2 for AD and AR programmes.

Table 13: Baseline global net production of wood commodities in age-class forests (excluding harvest losses) [Million m^3 Dry Matter per year]

Year	Wood production in age-class forests [Million m^3 Dry Matter per year]			
	Saw & Veneer logs	Pulp logs	Other industrial roundwood	Woodfuel
2005	1170	206	1678	202
2015	1486	226	1606	185
2025	1690	251	1710	210
2035	1831	281	1566	191
2045	1758	302	1439	195
2055	2025	343	1428	197
2065	1780	371	1383	195
2075	1873	400	1340	193
2085	1712	432	1397	192
2095	1512	466	1329	191

Table 14: Baseline regional net production of wood (excluding harvest losses) [Million m^3 Dry Matter per year]

Year	Wood production in forests per region [Million m^3 Dry Matter per year]									
	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	459	466	374	182	441	52	674	140	285	522
2015	537	496	387	172	470	60	696	264	302	518
2025	617	539	393	167	492	69	706	364	323	534
2035	669	569	383	156	495	78	692	514	343	545
2045	700	595	360	151	497	87	668	619	363	560
2055	720	604	331	145	492	97	628	719	371	579
2065	749	610	309	139	489	110	590	716	375	608
2075	766	611	710	132	479	124	546	280	371	634
2085	773	609	910	126	463	138	498	48	358	659
2095	768	603	877	118	441	153	448	42	339	681

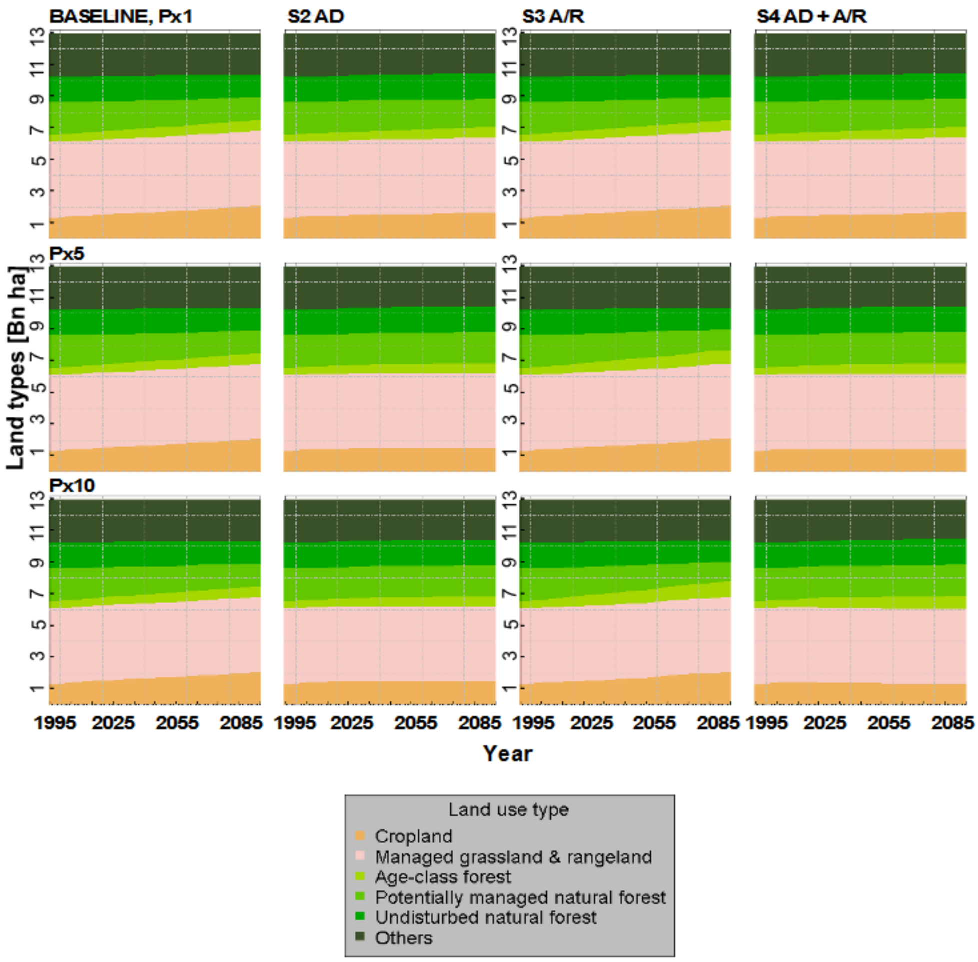

Figure 7: Land use changes across land types between baseline and scenarios from 1995 to 2095 at 11 US$, 55 US$ and 110 US$ per ton CO_2 (Billion hectares)

Table 15: Baseline regional consumption of wood [Million m^3 Dry Matter per year]

Year	Wood consumption per region [Million m^3 Dry Matter per year]									
	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	469	475	382	185	450	53	688	69	291	533
2015	566	522	407	181	495	63	733	72	318	546
2025	663	580	422	179	529	74	759	75	348	574
2035	743	632	425	173	550	86	769	77	381	605
2045	795	676	409	171	565	99	759	76	413	637
2055	837	702	385	168	572	113	731	73	431	673
2065	871	710	359	162	569	128	686	68	436	707
2075	890	710	332	154	557	144	635	62	432	738
2085	899	708	312	147	538	161	580	56	416	766
2095	893	701	292	138	512	178	521	49	394	792

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List of Acronyms

AD Avoided Deforestation

AgLU Agriculture and Land Use

AIC Akaike Information Criterion

ANCOVA Analysis of covariance

AR Afforestation and Reforestation

AR4 Fourth Assessment Report

BAU Business As Usual

BCEF Biomass Conversion and Expansion Factor

BEF Biomass Expansion Factor

BIC Bayesian Information Criterion

CAI Current Annual Increment

CFT Crop Functional Types

CGE Computable General Equilibrium

COMAP Comprehensive Mitigation Assessment Process

CLUE Conversion of Land Use and its Effects

DIMA Dynamic Integrated Model of Forestry and Alternative Land Use

FAO Food and Agriculture Organization of the United Nations

FARM Future Agricultural Resources Model

FASOM Forest and Agricultural Sector Optimization Model

FRA Global Forest Resources Assessment

G4M Global Forest Model

GAEZ Global Agro-Ecological Zone

GAINS Greenhouse Gas and Air Pollution Interactions and Synergies

GCOMAP Generalized Comprehensive Mitigation Assessment Process

GDP Gross Domestic Product

GDVM Global Dynamic Vegetation Model

GIS Geographical Information System

GLOBIOM Global Biosphere Management Model

GLC Global Land Cover

GTAP Global Trade Analysis Project

GTM Global Timber Model

ILUC Indirect Land Use Change

IMAGE Integrated Model to Assess the Global Environment

IMPACT International Model for Policy Analysis of Agricultural Commodities and Trade

IPCC Intergovernmental Panel on Climate Change

IUCN International Union for Conservation of Nature

KLUM Kleines Land Use Model

LEV Land Expectation Value

LME Linear Mixed Effect

LPJ Lund Potsdam Jena model

LPJmL Lund Potsdam Jena with managed land model

MAgPIE Model of Agriculture and its Impact on the Environment

MAgPIE-F Model of Agriculture and its Impact on the Environment including the Forestry sector

MAI Mean Annual Increment

MODIS Moderate Resolution Imaging Spectroradiometer

NPP Net Primary Production

NPV Net Present Value

OECD Organisation for Economic Co-operation and Development

PDF Probability Density Function

PE Partial Equilibrium

PES Payments for Environmental Services

PFTs Plant Functional Types

PV Present Value

RD Research and Development

REDD+ Reducing Emissions from Deforestation and forest Degradation plus the conservation of forest carbon stocks, sustainable forest management and enhancement of forest carbon stocks

REMIND Regional Model of Investments and Development

RIL Reduced Impact Logging

SFM Sustainable Forest Management

SRES Special Report on Emissions Scenarios

UNECE United Nations Economic Commission for Europe

UNFCCC United Nations Framework Convention on Climate Change

USDA United States Development Agency

WRI World Resources Institute

Declaration of primary authorship / Selbständigkeitserklärung

Ich erkläre, dass ich die vorliegende Arbeit selbständig und nur unter Verwendung der angegebenen Literatur und Hilfsmittel angefertigt habe.

Berlin, den 18.08.2014 Michael Krause